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by

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Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

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Monterey, California

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A GUARDED HOT PLATE METHOD FOR MEASURING THE THERMAL CONDUCTIVITY OF METALS AND NON-METALS

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This work is accepted as fulfilling

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ABSTRACT

The objective of this thesis was the design, assembly, and test of a guarded hot plate apparatus for the measurement of the thermal conductivity of metals and non-metals. Samples of naval brass, stainless steel, aluminum alloy, leather, soft rubber, corkboard, and asbestos slate were selected for the tests.

Values obtained for the thermal conductivity of stainless steel, naval brass (with the larger electrical inputs to the heat source), rubber, and leather were within ten per cent of tabulated values. Results for the other samples did not correspond to known values.

The experimental work was performed from January, 1958, through May, 1958, at the United States Naval Postgraduate School, Monterey, California. The author is indebted to Professors P. F. Pucci and C. P. Howard for their guidance during this project. Acknowledgement is due to Mr. N. Walker and Mr. A. B. Rasmussen for their assistance in the manufacture of the principal elements at the machine shop of the Naval Postgraduate School.

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TABLE OF SYMBOLS

A	cross-sectional area (sq. ft.)
c	specific heat (Btu/lb. ^{o}F.)
c_1	conversion constant, 3.413 Btu/hr. per watt
h	heat transfer coefficient (Btu/hr. sq. ft. ^{o}F.)
I	current (amperes)
i	current density (amps./ft.^{2})
k	thermal conductivity (Btu/hr. ft. ^{o}F.)
l	thickness of sample (in. or ft.)
q	heat transferred per unit time (Btu/hr.)
R	resistance (ohms)
T,t	Temperature (^{o}F.)
Δt	temperature drop (^{o}F.)
V	voltage (volts)
Δx	thickness of sample (in. or ft.)
δ	density of material (lbs./ft.^{3})
θ	time (hrs. or secs.)
$\mathcal{L}$	heat leakage (Btu/hr.)
ρ	electrical resistivity (ohms-ft. or ohms-in.)

NOMENCLATURE OF APPARATUS

Heater disc, disc - the central brass cylinder, three inches deep and four inches in diameter.

Guard ring, ring - the brass ring surrounding the heater disc, also three inches deep.

Cooling units - the two assemblies of brass plates and brass ring with interior baffles designed to carry the cooling water as the heat sink.

Baffle - Plexiglas strips installed in the cooling units to divert the water flow.

Heater cylinders - the brass cylinders, 3½ inches long and 3/4 inch in diameter, inserted in the heater disc to provide the heat source.

Guard ring heating element - a Calrod coil placed about the outside of the six inch diameter guard ring.

C-clamps - the large adjustable clamps with wing nut and threaded shaft used for holding the apparatus together.

1. Introduction.

The purpose of this project was the design, assembly, and test of an economical apparatus for the measurement of the thermal conductivity of metals and non-metals. Such a particular device could be utilized in the demonstration and study of heat transfer by conduction.

Schneider (1) states:

> The basic law which quantitatively defines heat conduction is generally attributed to the French mathematician Jean Fourier (1768-1830) ....The one-dimensional form of the Fourier law states that the quantity of heat dQ conducted in the x-direction of a homogeneous solid in time $d\theta$ is a product of the conducting area A normal to the flow path x, the temperature gradient $\delta t/\delta x$ along this path..and a property k of the conducting material known as the thermal conductivity. Expressed analytically,
>
> $$q = \frac{dQ}{d\theta} = -kA\frac{\delta t}{\delta x}$$
>
> in which the negative sign is arbitrarily affixed in order that Q be positive....The Fourier equation...for steady flow in linear conductors, where A does not vary with x, is:
>
> $$q = k\frac{A}{L}(t_1 - t_2)$$
>
> (L is the total thickness of the solid.)

The thermal conductivity, k, can be expressed as the quantity of heat per unit time that would flow through a one square foot area of a material when the temperature gradient equals one degree Fahrenheit per foot in the direction of flow. Values of k stated hereafter will be stated in the units of Btu/hr. ft. $^{\circ}$F.

A review of several references on the means of measuring k led to the following group from which one particular method was to be chosen: the guarded hot plate for non-metals (2) (3), Jakob's single plate system (4), Northrup's method using a second material with a known k (2),

Berget and Searle's cylindrical bar (5), Wilkes' long bar (2), Kohlrausch's method using the known electrical resistivity (5), Forbes' rod (5), and Mendenhall and Angell's uniformly heated tubes system (5). Choice of method is largely determined by the physical nature of the sample, the general temperature level to be maintained, and whether the sample is a good or poor thermal conductor.

Wilkes (2) describes the guarded hot plate method which has proved successful in measuring insulating and building materials and other non-metals. Two like samples are placed between a heat source and two water-cooled or refrigerant-cooled units. Heat leakage from the source is prevented with a guard ring kept at a temperature equal to the side temperature of the central heater. The apparatus is limited in its application to flat slabs of materials, a temperature range for the specimens of 32 to 1200°F., and for practical purposes to materials whose thermal conductivity does not exceed 0.42 Btu/hr. ft. °F. Disadvantages are the possibility of heat leakage at the edges of the samples, and irregularities caused by the air spaces between the heater, samples, and cooling units. This method will give only an average value of k over the range of temperatures between the hot and cold side of the sample.

Jakob (4) developed a single heater, sample, and cooling unit arrangement for the measurement of k of small-sized materials. Heat leakage was minimized by placing the entire assembly in a Dewar vessel. This is an elaborate method which can be used only up to moderately high temperatures, and with not too large a temperature difference between the inside and outside of the vessel.

Northrup (2) in his testing of insulating materials put a sample with an unknown thermal conductivity adjacent to one with the same cross-sectional area whose conductivity was known. The two slabs were placed between a steam-heated plate and a water-cooled unit. Knowing the temperature drop across each sample and the thickness of each, the unknown k is readily determined by the relation:

$$\frac{k_a \Delta t_a}{l_a} = \frac{k_b \Delta t_b}{l_b}$$

This method is simple and inexpensive; the actual rate of heat transfer need not be measured; but the reliability of the test depends on the previous establishment of the thermal conductivity of the sample used as a standard.

For good conductors, Berget (5) in 1888 developed the long bar method where a constant temperature gradient was to be obtained along the length of the rod. Condensing steam was used as the source of heat at one end, and an ice calorimeter was installed at the opposite end. The rod was surrounded by a guard cylinder of the same material as that being tested. Both rod and cylinder were subject to the same boundary conditions.

When steady state conditions were reached as determined by temperature measurements along the length of the bar, the temperature drops between the regularly spaced thermocouples were recorded. Knowing the cross-sectional area of the rod, distance between thermocouples, and number of calories transferred to the water, calculations for the k of the rod material could be completed.

Searle modified Berget's method with the use of an insulating sleeve in lieu of the guard cylinder. The disadvantage of some lateral heat leakage was still encountered. Wilkes (2) applied the principle of Berget and Searle in his design for testing the conductivity of metals. One end of the rod is threaded into a solid copper casting used as the heat source. The other end is inserted in a water calorimeter. Temperatures are measured at regular intervals along the rod. The rod is surrounded by an insulating sleeve, and the entire assembly is also inserted in an insulating guard tube. There have been good results obtained up to 1000°F. The possibility of heat leakage by radiation to the sleeve must be considered.

A very accurate means of determining the thermal conductivity is Kohlrausch's electrical energy balance method (5). The rod with unknown k is heated with a direct current supplied to a coil at the midpoint. Because the rod is insulated to prevent lateral heat leakage, the heat is conducted along the rod axis toward the ends which are kept at an equal temperature. At steady state conditions, the rate of conduction of heat towards an end equals the rate of electrical production of heat. Kohlrausch expressed this analytically as:

$$-k A\left(\frac{d^2T}{dl^2}dl\right) = I^2R = (iA)^2\rho\frac{dl}{A} = i^2\rho A\,dl$$

where $\frac{d^2T}{dl^2}$ is the change in the temperature gradient per unit length along the rod, ρ is the electrical resistivity of the rod, i the electric current density, I the direct current in amperes, and R the electrical resistance of the rod. Reducing and solving the differential equation gives :

$$T_m - T = \frac{i^2 \rho}{2k}(l_m - l)^2$$

where T_m is the maximum temperature at l_m, the midpoint of the rod, and l is the distance from one end of the rod to a position where the temperature is T. Since $i\rho(l_m-l)$ equals (V_m-V), the potential difference between l_m and l, solving for k in terms of readily measured quantities gives:

$$k = \frac{(V_m - V)^2}{2\rho(T_m - T)}$$

This method relies on the knowledge of the value of electrical resistivity and is limited to good thermal and electrical conductors.

Forbes (5) used an indirect method where the cylindrical rod is heated at one end and cooled at the other with no sleeve insulation. Lateral leakage must be considered in relation to the one-direction thermal conduction along the rod. Between two points along the rod, there is a variation in the temperature gradient per unit length. Using the law for thermal conduction, Forbes defined $\mathcal{L}$, the thermal leakage, as the heat loss equal to $k \cdot A \left(\frac{dT}{dl}\right)_1$ minus $k \cdot A \left(\frac{dT}{dl}\right)_2$ as measured at the two points. The value of $\mathcal{L}$ is found by cooling a similar rod by thermal leakage only from a temperature above the range of temperatures found in the test with the first rod.

Forbes showed that $\frac{d\mathcal{L}}{dl}$, the change in leakage per unit length equals $\left(-cA\delta \frac{dT}{d\theta}\right)$, the product of the cross-sectional area, A; specific heat, c;

density of the material, δ ; and change in temperature per unit time, $\frac{dT}{d\theta}$. Solving for $\mathcal{L}$, the value is substituted in the first relation to determine k for the material. It is specified that the rod have a large cross-section, that there be a large temperature gradient along the rod, and that the surface have a low emissivity for good results.

Mendenhall and Angell (5) developed a successful apparatus using long, uniformly electrically-heated tubes of nickel and aluminum placed in a water-jacketed, evacuated enclosure. Where the flow of heat is radial in passing across a tube of the sample tested, measurements of temperature and electrical input were made. Precise results have been obtained without the need for any guard ring or insulating sleeve. The elaborate precautions needed for the establishment and maintenance of a vacuum precluded further investigation of this method as a possible choice for the author's project.

Recent applications of methods for measuring thermal conductivity have been reported by Vestal and Fluker (6) and by Beck (7). Vestal and Fluker have used "heat meters" of pure bismuth to measure the heat flow through porous soils. This is a steady state method similar to Northrup's where a specimen of soil with unknown k is placed between two bismuth blocks, one heated and one cooled. The thermal conductivity, dimensions of the blocks, and temperatures at each face are all known so that the average heat flow, q, is readily computed at steady state conditions. Using the temperatures observed at the faces of the sample, and the calculated q, the k of the soil is found by Fourier's law. The advantage of better reproducibility of results is reported. Accuracy is dependent on the standard bismuth blocks. Periods of 150 to 400 hours were required to reach equilibrium conditions.

Beck (7) reported on a divided bar method for measuring the thermal conductivity of rocks. A steady state condition was established before insertion of a rock specimen between the warmer and cooler sections of the bar. After quickly inserting the sample, time to reach equilibrium conditions for a particular test was reduced to a maximum of twenty minutes. After a change in specimens, equilibrium could be regained in less than ten minutes. The procedure is also dependent on the known k of the brass bars and minimum heat leakage.

In the final selection of a method capable of determining the thermal conductivity of both metals and non-metals, consideration was given to the availability of materials, simplicity of design, and purpose as a laboratory demonstration for students studying heat transfer, as well as the inherent disadvantages of any one method.

The guarded hot plate apparatus offered a proven means for measuring the thermal conductivity of insulating materials. It is the generally accepted method and has been included in the standards of the American Society for Testing Materials (3).

The A.S.T.M. Standard C 177-45 specifies:

> For practical purposes, this method of test is limited to the determination of the thermal conductivity of materials having conductivities not in excess of 5.0 Btu inches per sq. ft. per hr. per degree Fahrenheit (0.42 Btu/hr. ft. °F.).

Wilkes in his introduction to thermal conductivity measurement methods points out (2):

> The k value for relatively good conductors is not determined with the same apparatus as that for good insulators.

The disadvantages of heat leakage, small temperature gradients across the sample thickness, the low emissivity of metallic surfaces, and

requirement for very flat surfaces at the faces of the samples to cut down contact resistance evidently have eliminated consideration of the guarded hot plate as a satisfactory means for measuring the k of metals.

It was the author's opinion that with due regard for these disadvantages while selecting the dimensions of the various parts of the apparatus, and choosing the positions for the various thermocouples to gain adequate temperature measurement and control of equilibrium conditions, satisfactory results could be obtained with one-inch thick metal samples as well as with thin slabs (approximately 1/8 inch thick) of insulating materials in a guarded hot plate assembly.

Limitations on the accuracy of the results from this method were imposed by the nature of the simplifications made. The cold water supplied for the heat sinks was not controlled automatically. The regulation of the temperature difference between the central heater disc and the guard ring was accomplished by manual control of two Variac transformers. Automatic regulation of cooling water flow by a thermostatic device and of the electrical inputs would permit only minor deviations in the temperatures at the various faces and edges when equilibrium conditions are approached.

Realizing the initial limitations in the control of varying temperatures, it was considered that the experimental errors would not be excessive in arriving at values of thermal conductivity for the samples sufficiently in agreement with tabulated values.

2. Description of equipment.

A symmetrical arrangement of one central heating disc surrounded by a guard ring, with two water-cooled plates for the heat sinks was designed as shown in Fig. 1. The apparatus as assembled is shown in Fig. 2. The principal components are further pictured in Fig. 3.

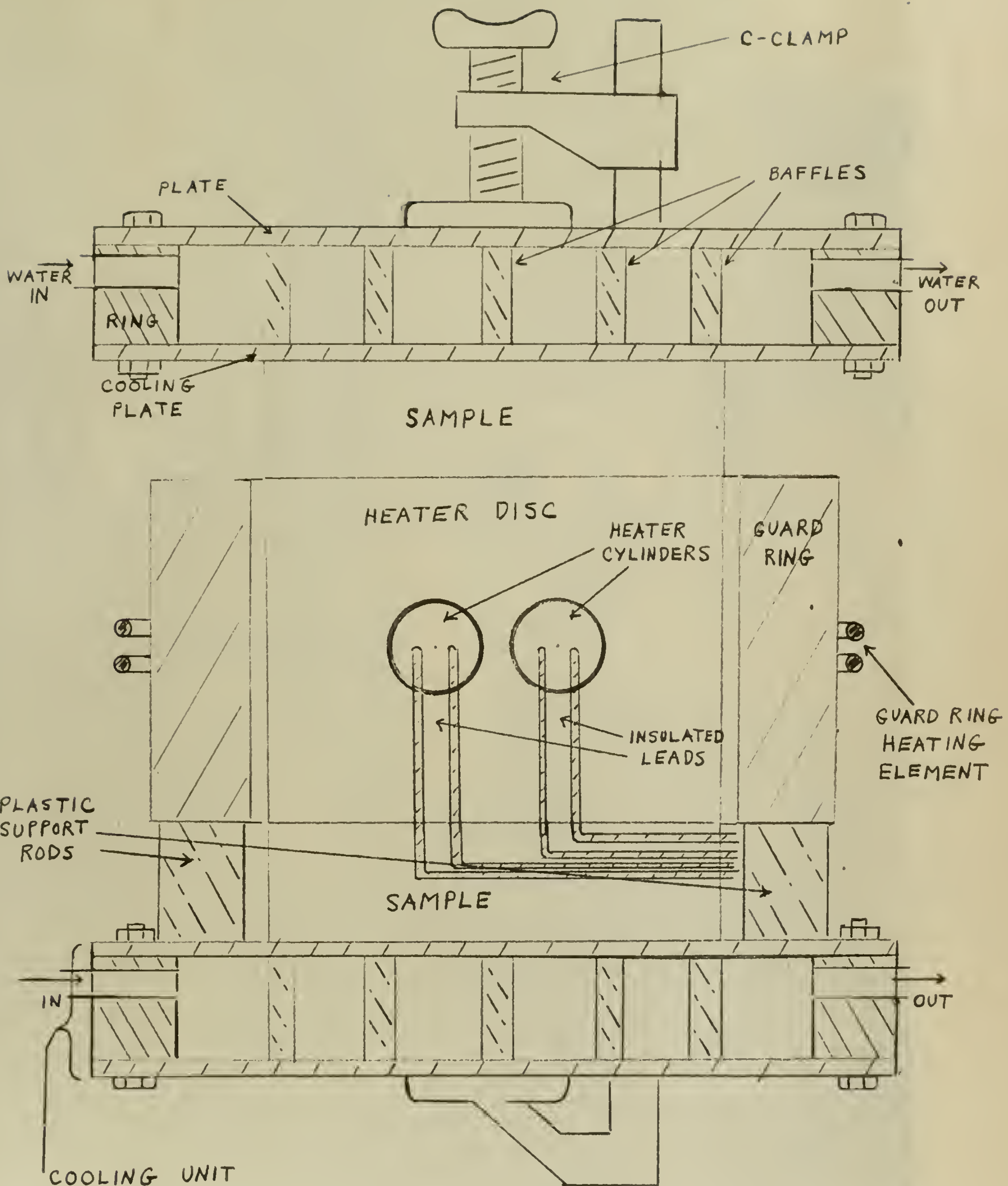
a. Heaters and cooling units.

A readily available good thermal conductor, naval brass, was selected as the material for the heater disc, guard ring, and cooling plates.

In the design, the temperature range was limited by the maximum output of the cylindrical heaters inserted in the central heating disc and by the cooling water temperature. The higher temperature was also dependent on the particular sample inserted in the apparatus. Relatively small inputs to the heaters could give temperatures of over 500°F. at the heater disc face adjacent to an insulator.

Two Chromolox 250-watt cylindrical heaters, 3/4 inch diameter and 3½ inches long, model number C-503C, manufactured by E. L. Wiegand Co., were available for insertion in the three-inch long, four-inch diameter brass disc. The central disc, guard ring, and two brass samples were all machined from naval brass round bar stock. In the disc two parallel holes were bored with a tight slip fit specified for the heater cylinders. The two insulated leads from each heater came out via the 0.1 inch air gap between the disc and guard ring.

The guard ring had its own source of heat supplied from a salvaged Calrod heating element coiled 2½ times about the outer edge. The guard ring was three inches long, six inches in outside diameter and 4.2 inches inside diameter. This provided the 0.1 inch gap all around the central heater disc.



3/4" = 1 INCH

GUARDED HOT PLATE ASSEMBLY

FIGURE 1

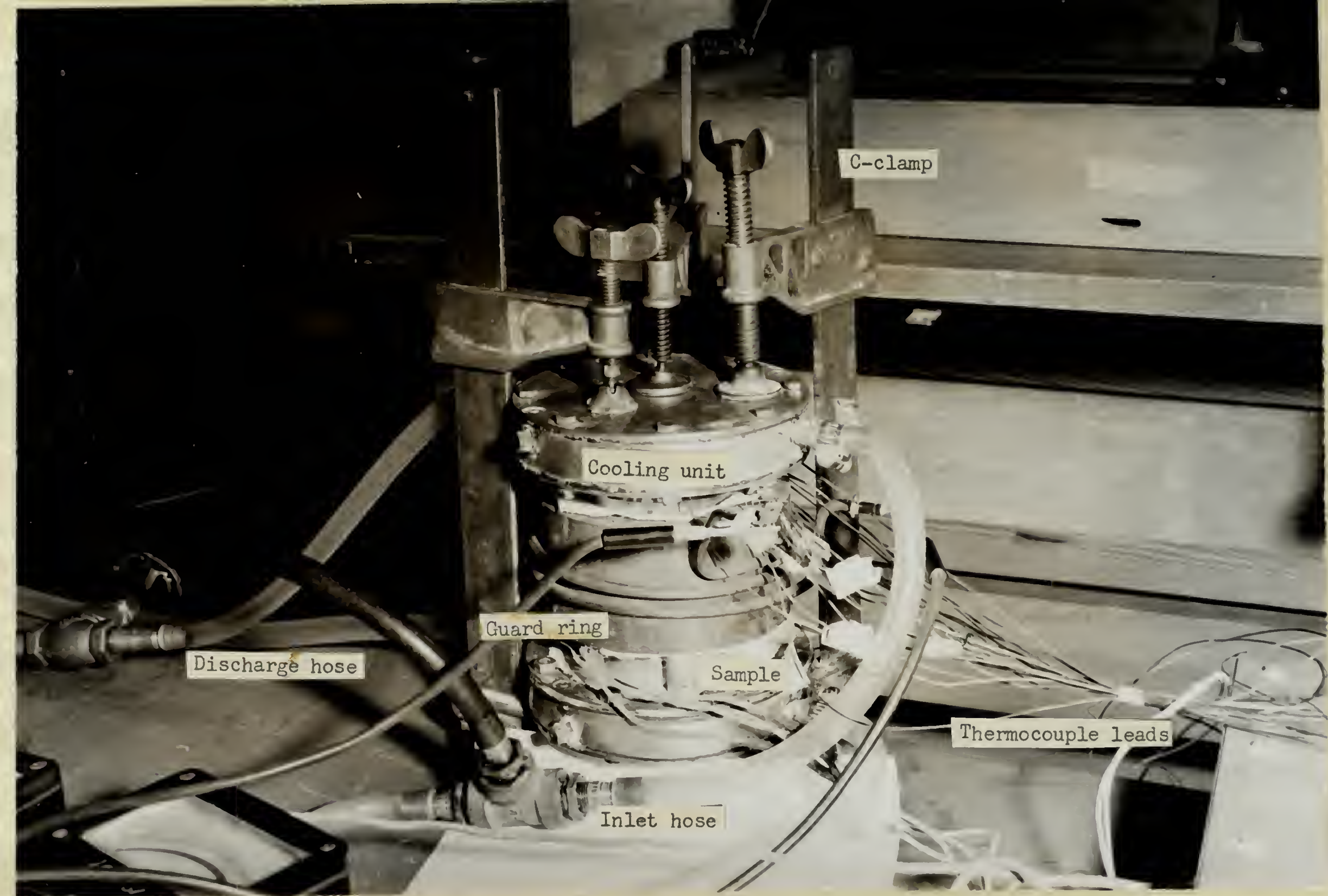


Figure 2. View of Assembled Apparatus

Figure 3. View of Principal Components

The one-inch thick, four-inch diameter metal samples were placed on opposite faces of the disc. In contact with the samples were two cooling units with faces of seven-inch diameter naval brass plates. Each plate was bolted to a seven-inch outside diameter, $5\frac{1}{2}$-inch inside diameter ring, one inch in height, and a similar brass plate on the opposite side of the ring. Gaskets were inserted between ring and plates to seal the "sandwich". Inlet and outlet fittings for each cooling unit were inserted in the seven-inch rings with the center of the fittings close to the top of the ring. This was done to avoid trapping air pockets in the units above the entrances and exits.

To reduce the temperature gradient in the water as it passed across the plate adjacent to the heated samples, baffles were required to properly interrupt the flow. The first design called for a series of aluminum baffles 3/4 inch high - some secured to a thin aluminum plate resting against the brass plate adjacent to the samples, and the others secured to a similar plate resting against the opposite brass plate in the "sandwich". Shoulders on the faces of the ring in the water unit prevented the baffles from moving when in place. However, as effective as the baffles were in obstructing the direct flow of water, they did not permit continuity for a force applied on the exterior of the cooling units to reach the samples and the central disc. Any clamping pressure could only be transmitted through the ring of the cooling units. By inserting a light layer of grease on the sample faces, it was found that the contact between samples and cooling plates was made only at the outer edge of the samples.

To remedy this unsatisfactory condition, new baffles were cut from one-inch wide, $\frac{1}{4}$-inch thick Plexiglas strips. Careful measurements of the

exact gap between the plates in the cooling units were made and the plastic strips were cut to within 0.001 inch of the measured gap. The strips were cemented to the plate farthest from the sample in a staggered formation as shown in Fig. 4. On clamping the apparatus, the clamping force was transmitted through all the Plexiglas strips insuring better contact between samples and the heating disc.

The cooling water was taken directly from the cold water system. Through clear plastic tubing, ½-inch inside diameter, the water was led to each of the cooling units and returned to the sink. Globe valves were installed in the discharge lines to control the flow of water. Maintaining essentially the same cooling plate temperatures for each unit was possible with these control valves.

Elaborate methods of maintaining the coolant temperature at a desired level have been described by the National Bureau of Standards (8). In the simplification of this apparatus, the variation in cold water temperature was accepted. Generally, the water temperature measured about 62 degrees Fahrenheit with an estimated deviation of 0.1 degree as indirectly observed at any one thermocouple location on the cooling plates. For a particular run, it was found necessary to take readings for at least an hour before the cold water temperature stabilized.

b. Electrical circuits.

For the control of the disc heaters and guard ring heating element, two General Radio 115 volt, 50-60 cycle, Variac transformers were used. In each of the two electrical circuits, the following instruments were used to measure the electrical input: 0-150 volt AC voltmeters, 0-10 amp. AC ammeters, and 0-750-1500 wattmeters. A 0-250 wattmeter was used for the low input runs testing the non-metal samples. The circuit

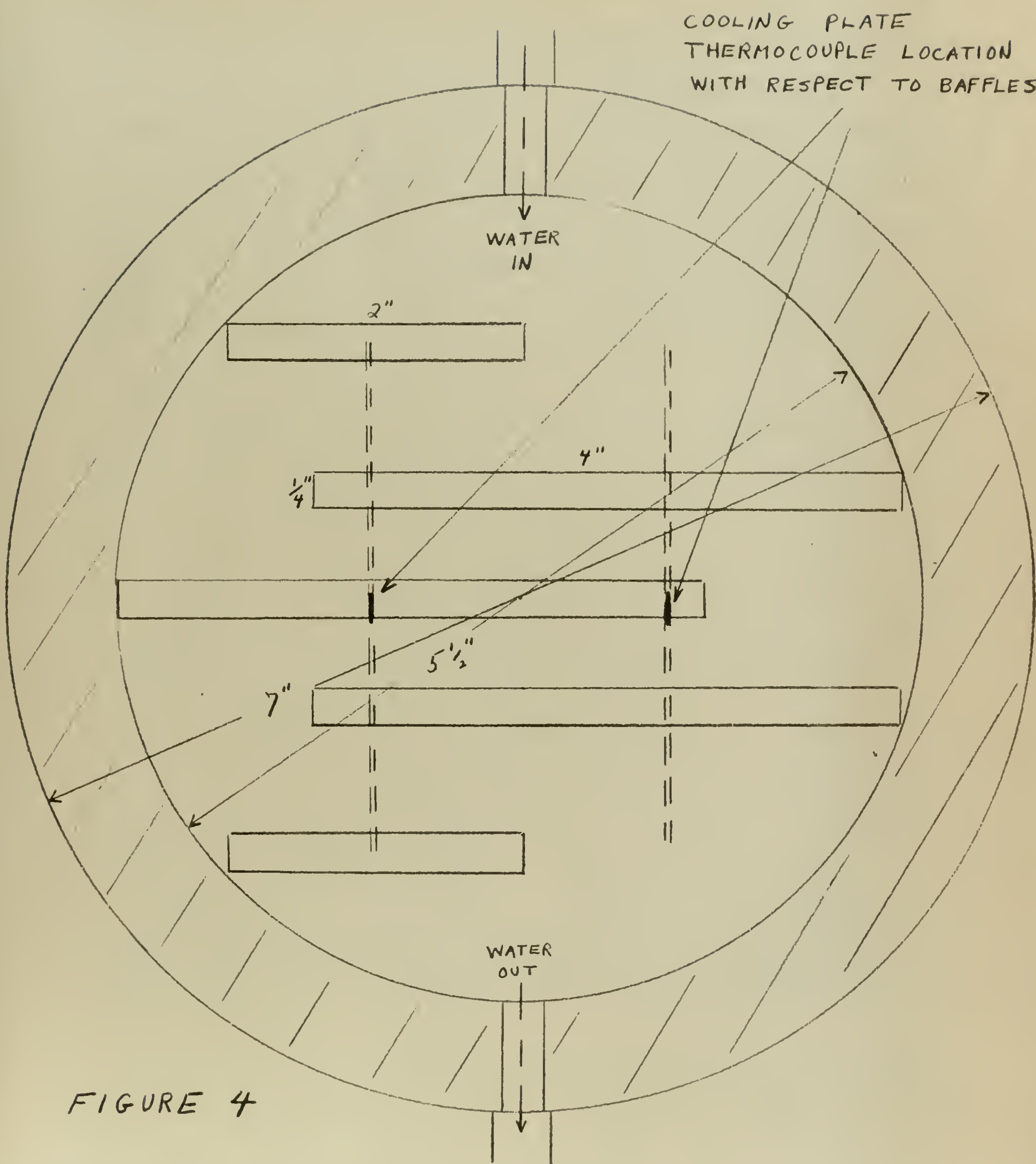


FIGURE 4

BAFFLE ARRANGEMENT IN COOLING UNIT

for the two cylindrical heaters (inserted in the central heating disc) included two double-pole double-throw switches wired to permit operation of the heaters in series or in parallel. (See Figs. 5 and 6). For the observations with the metallic samples, the maximum available electrical input of 500 watts was obtained by placing the two 56 ohm resistances in parallel. Switching the two heaters in series gave a total resistance of 112 ohms. This resulted in a lesser electrical input for the same voltage and thus careful regulation of the input for the runs with insulating materials.

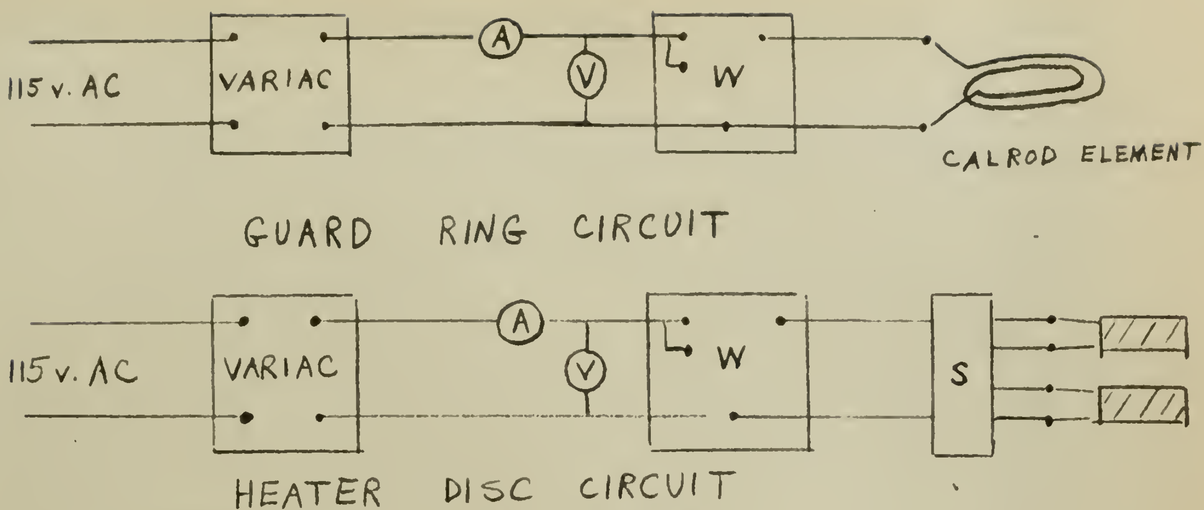
The resistance of the Calrod element around the guard ring was measured at 13.5 ohms. For the metallic samples, it was found that the input to the ring element varied between $\frac{1}{4}$ and $\frac{1}{2}$ of the disc heater input while maintaining the same temperature on the side of the disc and the inside of the guard ring. The input to the ring element was equal to or slightly greater than that to the disc heaters for the non-metals.

c. Metallic surfaces.

For the surfaces of the cooling plates, the heater disc, and the metallic samples, the A.S.T.M. specification for flatness, as stated in the guarded hot plate description (3), was followed as a guide:

> The heater plates and cooling plates of any type of apparatus for good results should have at least 90 per cent of the surface in a true plane with no depression having an area greater than one per cent of the total and a depth (excepting slots) greater than 0.003 inches.

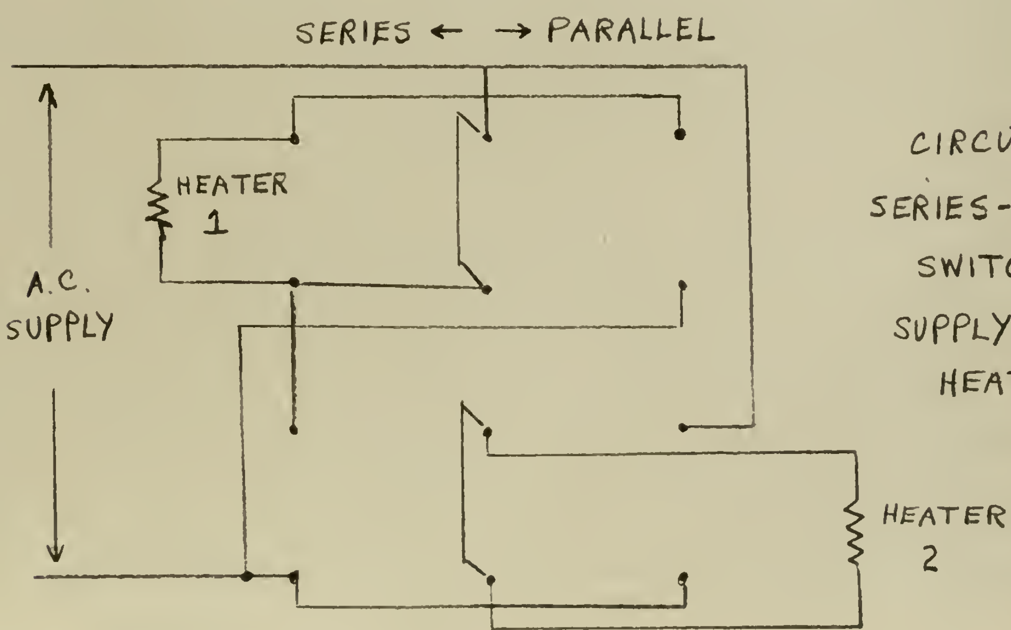
All the surfaces were machined smooth and then successively lapped with Clover lapping compound, grades C, 1-A, and 3-A (in order of increasing fineness of grit). The surfaces were viewed under a sodium vapor light and a DoAll A optical flat. Lapping was continued until the interference fringe pattern became clearly evident on the faces. It is



A - AMMETER W - WATTMETER

V - VOLTMETER S - SERIES-PARALLEL SWITCHES (SEE FIG. 5)

FIGURE 5



CIRCUIT FOR SERIES-PARALLEL SWITCHES IN SUPPLY TO DISC HEATERS

FIGURE 6

estimated that deviations were on the order of 0.001 to 0.0001 inches across a face.

For the metals under investigation, one-inch thick samples were cut from the four-inch outside diameter bar stock readily available at the Naval Postgraduate School shops. Alloys used were naval brass (60% copper, 39¼% zinc, and 0.75% tin); stainless steel - A.I.S.I. #304 (18% chromium, 8% nickel, 0.08% carbon, 2% manganese, balance iron); and aluminum alloy 61S (1% magnesium, 0.6% silicon, 0.25% copper, 0.25% chromium, balance aluminum).

d. Non-metallic samples.

Materials chosen for the tests of non-metals were soft rubber, sole leather, corkboard (with the fiber backing peeled off to obtain a more pliable sample), and asbestos sheet. The samples were purposely obtained from readily available thin sheets in order to obtain smaller temperature differences across the sample thickness. Establishment of a large temperature drop at steady state conditions would require an excessive period of time for any one run.

Thickness measurements were made with the samples in place but partly removed from the gap between disc and cooling plates. A feeler gage was used to measure the gap distance after the clamping pressure was applied. A second check of the thickness was made with a small piece of easily-compressed solder left in the gap adjacent to the partly exposed sample. The piece was then removed and measured with the one-inch micrometer.

e. Temperature measurement.

Exacting requirements on the accuracy of the temperatures measured were necessary due to the appreciable deviations encountered when using the results in the thermal conductivity calculations.

The following is a sample calculation for the naval brass sample showing the magnitude of the quantities measured:

The actual thickness of the sample was measured by micrometer to the nearest 0.001 inch. In the grooves for thermocouples in each face of a sample, a depth of 0.025 inches was provided. Assuming that the thermocouple beads were centered in each groove, a correction of half the depth is made for each groove in calculating the thickness.

Measured thickness = 0.999 inches.

Correction for grooves = 2(0.0125) = 0.025 inches.

Assumed thickness = 0.974 in. = 0.0812 ft.

An accurate ruler was used to measure the sample diameter to the nearest 0.01 inch. Electrical input in watts was converted to Btu/hr. by the factor of $c_1 = 3.413$ Btu/hr. per one watt. Since the conversion factor, thickness, and area were constant for any one sample, a multiplying factor for use in Fourier's equation, $k = \dfrac{c_1 q \Delta x}{A \Delta t}$, was derived as follows:

$$\Delta x = 0.0812 \text{ ft.}$$

$$A = \frac{\pi d^2}{4} = \frac{\pi}{4}\left(\frac{3.99}{12}\right)^2 = 0.0864 \text{ sq. ft.}$$

$$\frac{c_1 \Delta x}{A} = \frac{(3.413)(0.0812)}{(0.0864)} = 3.21 \text{ Btu/hr. ft. watt}$$

Entering the temperature drop across the sample, Δt, and the electrical input in watts, q, for a particular run gives:

$\Delta t = 3.23^\circ$F.

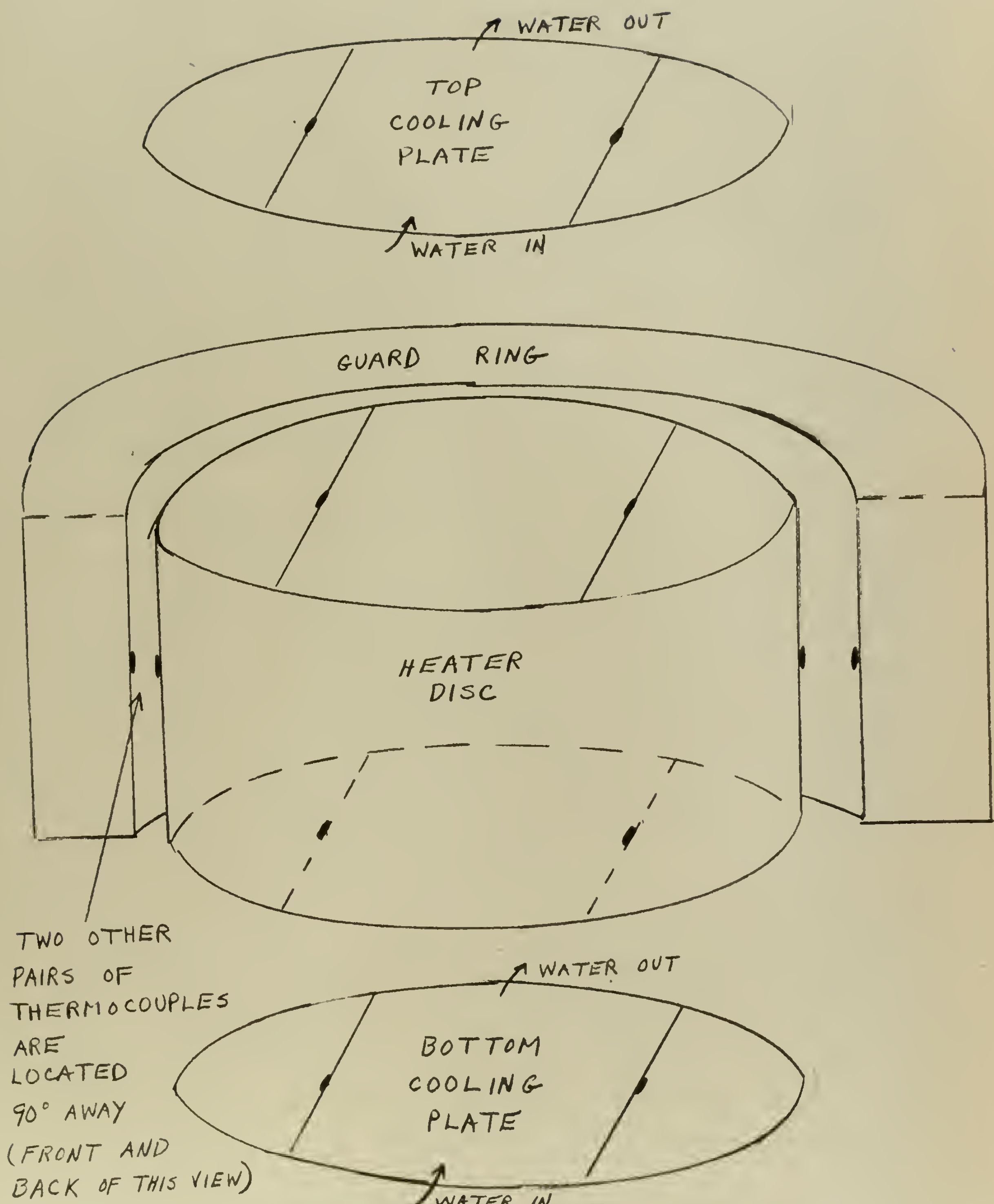
$q = 100$ watts

$$k = (3.21)\left(\frac{50}{3.23}\right) = 49.7 \text{ Btu/hr. ft. }^\circ\text{F.}$$

(One-half of the input supplied to the cylinders is assumed to flow in each direction normal to the sample faces. Equivalent temperatures at the top and bottom faces of the heater disc and at the two cooling plates substantiated this assumption.)

Brown and Sharpe gauge 30 copper-constantan thermocouple wire was selected because of its small size and sensitivity in the range of temperatures (0-400°F.) anticipated in the tests. Beads at one end of the thermocouples were formed by flash welding in a mercury filled U-tube. Approximately 30 volts AC supplied to the tube provided a satisfactory potential for the process.

Grooves 0.040 inches wide and 0.025 inches deep, slightly larger than the two thermocouple wires stripped of the exterior fiberglass insulation, were cut in each face of the heating disc and each cooling plate. These grooves were placed parallel and one inch on either side of the center of the faces. The thermocouple ends with the exterior insulation stripped back were placed in each groove and cemented in place with General Electric glyptal cement #1286. Early attempts to solder the beads in the grooves proved unsuccessful as the metal surface transferred the heat from the soldering iron too quickly to permit the solder to flow into the shallow grooves. In the latter stages of the tests, the solid solder was cut in very small sections and then carefully pressed into the grooves around the thermocouple beads. Use of the solder insured the contact of the bead with the surface. The original arrangement of the thermocouples is indicated in Fig. 7. One thermocouple was placed in each groove of each cooling plate. One each was fixed in the grooves on the disc faces.



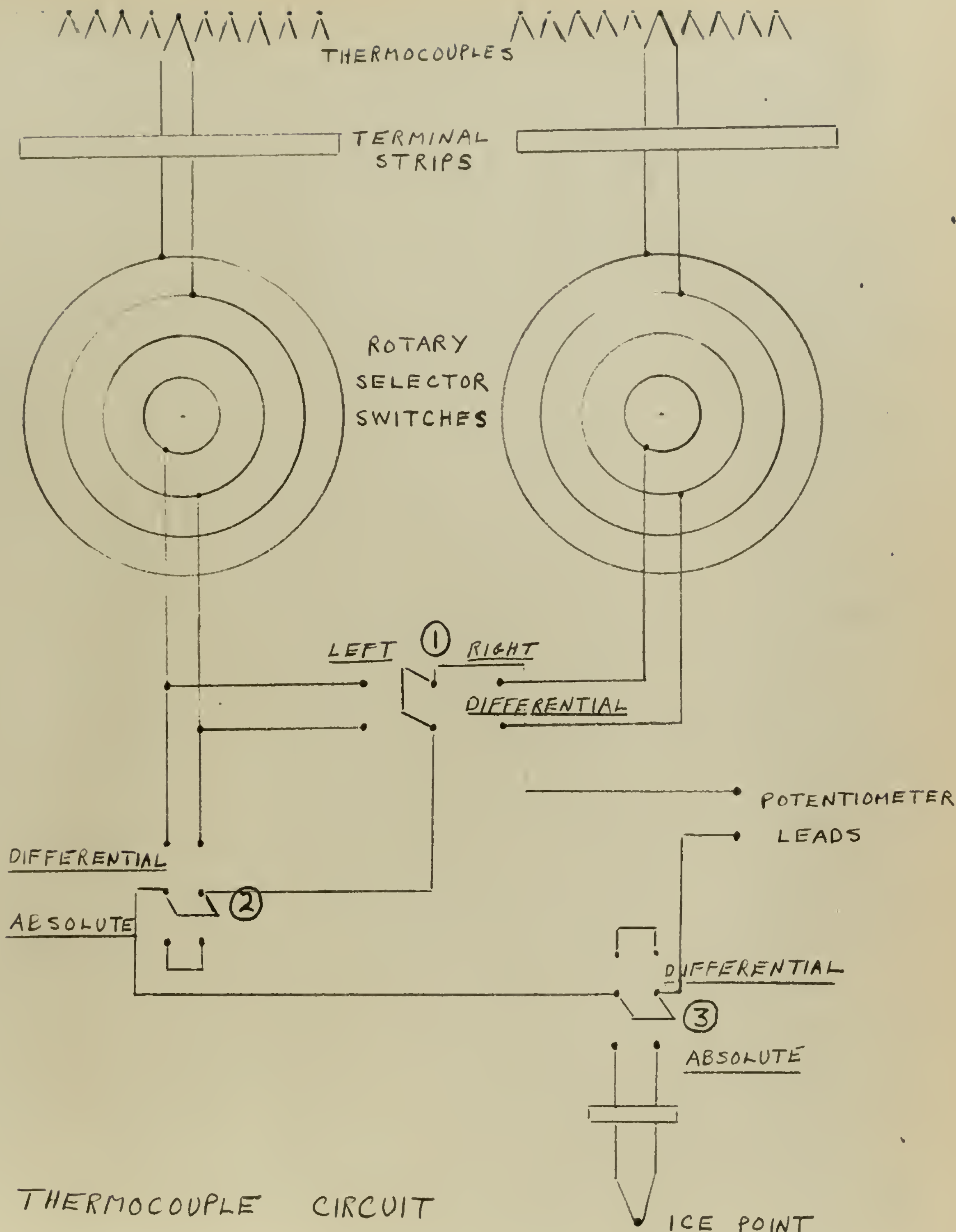
ORIGINAL THERMOCOUPLE LOCATION
NOT TO SCALE

FIGURE 7

Four thermocouples were cemented to the sides of the disc, with four more arranged on the inner circumference of the guard ring for comparison with the disc thermocouples. To achieve steady state conditions for any particular test, the four ring temperatures were matched to the four disc temperatures while the drop in temperature across the samples remained constant. Later in the tests, only two pairs of thermocouples were used to check the equilibrium between disc and guard ring temperatures, as other thermocouples were relocated directly on the sample faces.

To enable quick reading of any thermocouple compared to an ice point at 32°F. or selected differential readings between two thermocouples, the circuit including two Leeds and Northrup 11-position rotary selector switches was designed as shown in Fig. 8. The thermocouple at 32°F. was centered in a thermos filled with ice water. Each copper lead and each constantan lead were brough to adjacent terminal blocks on a panel sufficiently removed from the apparatus to be effectively at room temperature at all times. One double-pole double-throw switch permitted the choice of either the left hand selector switch or right hand one when the two other similar switches were in position to place the ice point in the circuit.

With switch number one thrown to the position marked DIFFERENTIAL in Fig. 8, and the other two turned to their alternate positions, also labelled DIFFERENTIAL , any thermocouple connected to the left selector switch could be matched against any one of those connected to the right selector switch to obtain differential readings. For the early test runs, a portable Rubicon potentiometer with a combination pointer and reflecting galvanometer was used. Each millivolt reading was obtained by balancing the potentiometer voltages by manual control.



THERMOCOUPLE CIRCUIT

FIGURE 8

To speed up the recording of the numerous readings, the Honeywell Brown Electronik potentiometer with automatic balancing unit was substituted in the temperature recording circuit. Accuracy of the Brown potentiometer is estimated to be plus or minus five microvolts.

In the latter tests, a check on the sensitivity of the Brown potentiometer was incorporated by using the Rubicon precision potentiometer and Leeds and Northrup wall-mounted precision galvanometer. Incorporated with this potentiometer were a six-volt storage battery and a recently calibrated (March, 1957) standard cell. The precision equipment permitted readings to the nearest 0.1 microvolt.

f. Clamping arrangement.

To hold the assembly together, two circular flat plates were designed to fit over the cooling units. Two 5/8-inch diameter brass rods, $9\frac{1}{4}$ inches long, were threaded in place in the lower aluminum plate on opposite sides of the assembly. The upper plate was placed over the top unit and bolted in place with hex nuts on the projecting rods. The tightening of the nuts by wrench effectively clamped the assembly. Since the plates were subjected to a maximum tension near the rods which were 3 3/4 inches from the center of the assembly, the maximum force was exerted at the outer edge of the cooling units. This brought the cooling units and the rim of the samples into good contact, but gave poor contact closer to the center of the samples. As outlined earlier, Plexiglas baffles were inserted in place of the metallic baffles to provide a means of transmitting pressure to the contact surfaces without disturbing the flow of heat into the cooling plate. However, this did not alleviate the problem of poor contact between sample faces and the cooling units.

The clamping plates and brass rods were set aside in favor of four large Hargrave C-clamps. These had a maximum distance between jaws of 14 inches. Placed in a pattern around the assembly, these clamps provided satisfactory contact between samples, cooling units, and the center heater disc. This was indicated by the nearly equal temperatures measured by different thermocouples on any one face. The clamps were only tightened hand-tight, as further tightening with a wrench did not change the existing readings noticeably.

The guard ring was supported independently by three one-inch long, 3/4-inch outside diameter rods made from an excellent wood-filled insulating plastic placed on the lower cooling unit. The ring was thermally insulated from the cooling units by these pieces and kept from touching the center disc by strips of Raybestos gasket material, 1/16 inch thick, and by the lead wires from the cylindrical heaters. (See Fig. 1.)

The entire assembly was insulated by a loose-fill insulating powder. Johns Manville "Sil-o-cel C3", a diatomaceous silica base powder, was selected for packing into a one-foot square plywood box after the apparatus and clamps were in position.

3. Assembly and test of apparatus.

In every test run, a chosen electrical input was selected for the cylindrical heaters in the center disc. The input to the guard ring heating element was adjusted until the temperatures of the inner circumference of the ring approached that of the side of the central disc. Meanwhile, maximum flow of water from the cold water faucet was maintained. Some throttling of the flow coming from the upper cooling unit was normally necessary to maintain the temperatures on the two cooling plates within two degrees. By tilting the apparatus slightly so that the water outlets were higher than the inlets, better circulation was obtained with more stable cooling plate temperatures.

The original testing of the apparatus was done with a one-inch thick center heater disc and accompanying one-inch thick guard ring. It was readily apparent that a larger disc was required to allow the heat flow to become more uniform at the faces of the disc. The temperatures measured at the faces of the one-inch disc showed no relationship to one another, indicating a non-uniform temperature gradient existing across the samples.

With the lapped three-inch thick heater disc and three-inch guard ring, the naval brass samples were first placed in the assembly in metal-to-metal contact with the disc and cooling plates. For low electrical inputs, the cooling plate temperatures were above the anticipated values. On further study of the original design of the baffles in the cooling units, it was found that the thin (1/16 inch) aluminum plate, to which half of the baffle strips were secured, and which was resting against the cooling plate inside the "sandwich", was providing an excellent conducting path for the heat flow before it reached the cooling water.

By removing the two plates and attached baffles, there was no metallic path for the heat conduction through the samples, cooling plates, and water. However, half of the first baffle arrangement had been discarded. The temperatures at the cooling plates then approached 70°F. for the low heat-input runs. This baffling arrangement was subsequently superseded by the strips of one-inch Plexiglas as shown in Fig. 4.

The inlet and outlet of each cooling unit was placed approximately 90 degrees apart in the first tests. A Plexiglas cover for the top cooling unit was substituted for the brass plate so that the flow of water through the unit could be observed. In this way, it was found that the flow, although somewhat turbulent, left stagnant areas in the "sandwich" on the side away from the inlet and outlet connections. Optimum conditions were obtained by placing the outlet 180 degrees away from the inlet. Water passing around the staggered arrangement of Plexiglas baffles left no apparent stagnant areas. Temperatures measured at the two points one inch either side of the center of the cooling plates showed variations of less than two degrees. As the water warmed up in passing across the cooling plate, a parallel rise was expected in the temperatures measured at the plate surface.

Pressure to hold the parts of the apparatus together was applied by tightening the wing nuts on the four Hargrave C-clamps. The four clamps were placed as close to each other as clearance for tightening the wing nuts permitted.

It was not the original intention to place thermocouples on the metallic samples. The temperature drops between the heater disc and the

cooling plates were considered to be very close to those across the samples. As difficulties arose in reaching a temperature difference across the sample thickness which even approached expected values, four thermocouples were placed on each face of one of the naval brass samples to check the temperature distribution. Parallel grooves placed one inch on either side of the sample center were cut to match the groove arrangement on the cooling plate and heater disc faces. Two thermocouples were placed in each slot, and connected to the terminal strips so that those directly opposite each other on the two faces of the sample could be read differentially.

Placing the heater, samples, and cooling plates in direct contact and clamping the assembly with the original arrangement of the two clamping plates and connecting rods, the temperature drops across the air film between the heater disc and sample and across the film between the sample and cooling plate each amounted to about twice the drop across the brass sample itself. With the C-clamps in place as the substitute for the first arrangement, temperature differences at the interface equalled about one-fifth of the drop across the sample.

In reference to the guarded hot plate apparatus, Worthing and Halliday state (5):

> Ordinarily the chosen sources and sinks...for thermal currents are good conducting metallic solids. The attempt is made by their use to insure that at least two chosen surfaces of the poor conductor (the sample in this instance) in any one case shall be at known, constant temperatures. Unfortunately, these surfaces are not always in good direct contact with the metallic sources and sinks. If a minute film, whether or not it contains air is immaterial, separates the specimen being studied from the source or the sink for an appreciable part of the assumed contact area, the average temperatures of the separated parts will differ appreciably. Often, but not always, this difficulty may be overcome by covering the contact surfaces with a liquid such as an oil or water.....Could the liquid chosen be without

effect on the nature of the poor conductor, as for oil or water on glass, and have the same thermal conductivity as the poor conductor being studied, the contact problem would be completely eliminated.. Since the film is usually relatively very thin, the second condition is ordinarily of little consequence. In so far, however, as there is failure to achieve these two conditions, the results obtained, for cases where the assumption is made of a common temperature of source or sink and adjacent conductor surface, are open to some question.

Reams and Spry (9) in their investigation of heat transfer modes across a flat metallic interface encountered the same problem where the "actual" metallic contact area was considerably less (on the order of 1/10,000) of the apparent contact area. Calculations of thermal conductivity are then based on a combination of the conduction through the minute points of metallic contact and the conduction through the air or other medium between the sample and heater disc and between the sample and cooling plate. Thermal convection is considered negligible due to the small distance between the metallic surfaces. Spry and Reams showed in their experimental work that the proportion of heat transferred across the interface by radiation is negligible.

An excellent means for eliminating the air film would be placing a highly conductive liquid metal at the interface. Mercury with a k of 4.8 Btu/hr. ft. ^{o}F. would suffice. The danger and impracticality of handling mercury nullified its consideration for this apparatus. At the range of temperatures chosen for these tests - room temperature to 300^{o}F. - a relatively high conductive grease was first tried as a filler for the interface. The ease in applying a thin film of Dow Corning high vacuum silicone grease influenced the decision to use a grease. With the grease layer or the other materials later used for the same purpose, it

became mandatory to know the temperatures on the faces of the samples for comparison with those measured at the heater disc and cooling jacket faces. The temperature gradient with the grease at the interface was determined as 2.6 - 2.8°F. with 50 watts input to the sample.

Neither the grease layer or the 0.060 inch thick layers of rubber gasket material proved to be satisfactory in contact with the faces. Though the air film was supposedly eliminated under the clamping pressure, the resulting temperature gradient across the sample itself was still too large for satisfactory proof of this design for a guarded hot plate method. Calculated values of the thermal conductivity of the naval brass were one-half of the expected results.

In Wilkes' description of the guarded hot plate method, he points out (2):

> The emissivity of the heater, guard, and water-cooled plates must be high (approximately 0.9). It can be made so with a high-emissivity paint, or, better still, by attaching asbestos paper or similar material to the metal surfaces. There is always a resistance to heat transfer from one surface to another unless the thermal contact is perfect. This perfection is never realized in thermal contact between a metal plate and a rigid insulator, and consequently, air pockets occur between the two surfaces. The resistance to heat flow across these pockets depends upon the conductivity of the air and radiation. The radiation is minimized by means of low-emissivity surfaces, such as copper or aluminum, which also results in greater resistance to heat transmission from the metal surface to the insulation. Since, in practice, insulation generally faces high-emissivity surfaces, such as wood, plaster, and brick, it is now recognized that determinations with the plate test should be made with high-emissivity surfaces. Many of our early published k values were made with polished aluminum, brass, or copper plates, and the values are undoubtedly somewhat lower than would be obtained for the same materials with high-emissivity plates as required today.

The emphasis on protecting the polished metal faces from each other with a highly emissive substance led to procuring thin discs of asbestos paper (thickness of 0.018 to 0.019 inches uncompressed) for insertion

between the disc and samples, and between the samples and cooling plates. The results of the latter tests are outlined in the following section.

The A.S.T.M. Standard C177-45 (3) specifies that:

> The edge insulation shall be of any convenient loose-fill or blanket-type insulating material to reduce edge losses from the heater plate, test specimens, and cooling plates. It shall be of such thickness that the resistance to edge losses shall be at least twice and preferably three or more times the thermal resistance of the specimen in the direction of normal heat flow.

The insulating powder was used to pack around the entire apparatus in early tests with the naval brass samples in the assembly. It was then determined that there were no appreciable changes in the thermocouple readings whether or not the apparatus was packed in the powder.

Using a simplified relation as stated in McAdams (10) for the heat transfer coefficient, h_c, in Btu/hr. sq. ft. $^{\circ}$F., for natural convection from a horizontal cylinder:

$$h_c = 0.27\left(\frac{\Delta t}{D_o}\right)^{0.25}$$

For a particular run, the Δt between the average sample temperature and ambient air was 25°F. Measuring D_o , the outside diameter of the sample, as 0.333 ft., the value for h_c in this case was:

$$0.27\left(\frac{25}{0.333}\right)^{0.25} = 0.795 \text{ Btu/hr. sq. ft. } ^{\circ}\text{F.}$$

The magnitude of this coefficient of heat transfer from the brass to ambient air is three orders of magnitude smaller than the corresponding thermal conductivity of brass per one-inch thickness.

$$\frac{k}{\Delta x} = \frac{69}{1/12} = 828 \ \text{Btu}/_{\text{hr. sq ft. °F.}}$$

Ambient air surrounding the good conductor is an effective insulator.

For the tests of the metallic samples reported in the next section, no insulating powder was used. This considerably shortened the time required for setting up and disassembling the apparatus.

For each run, the electrical inputs measured by the wattmeters in the two circuits and all the thermocouple readings measured relative to the ice point were recorded. In addition, the differential readings for each pair of thermocouples placed opposite to each other on the faces of the metallic samples were recorded. The latter readings varied up to 0.1 millivolts from the result of subtracting the absolute readings of one of the thermocouples measured relative to 32°F. and another similarly measured.

As a check of the differential readings as recorded on the Brown Electronik automatic balancing potentiometer, the same temperature differences were measured with the precision potentiometer and galvanometer arrangement. The two readings for the same pair of thermocouples compared within one to two per cent.

Each copper-constantan thermocouple gave a potential reading in millivolts which was then converted to degrees Fahrenheit with the aid of Leeds and Northrup tabular data (11) based on zero millivolts equals 32.0°F. Interpolations were made to the nearest tenth of a degree.

For the conversion of the differential readings, the average difference between two adjacent values in the tables was obtained over the range of absolute temperatures measured. This was divided into the millivolt reading to give temperature differences to the nearest tenth.

Two conditions were the ultimate objective in each test run. First, no changes in the absolute readings and differential readings for the samples should occur between successive readings. Second, the temperatures of the edge of the heater disc and the guard ring inner circumference should be equalized. Due to time limitations and the absence of automatic control of the electrical inputs and cooling water, ideal steady state conditions could only be approximated.

During the start of a particular run, the guard ring with its exterior heating element warmed up at a slower rate than the central heater disc. The measured temperature drops across the samples continued to rise until the guard ring temperatures approached those on the side of the disc. These temperature drops remained nearly constant if the guard ring temperatures were equal or slightly higher than the corresponding disc temperatures. Normally, the average guard ring temperature was kept up to three degrees warmer than the average temperature on the side of the heater disc. This guarded against any of the heater disc input being transferred laterally to the guard ring.

A study of temperatures across the guard ring was made in conjunction with the scheduled tests to determine how the guard ring element acted in maintaining the desired temperature at the inner circumference. Holes of 0.070 inches diameter were drilled in the face of the guard ring. One series of holes $1\frac{1}{2}$ inches deep was placed in a line spaced as shown in Fig. 9. The other series was placed about 135 degrees away from the

GUARD RING - PLAN VIEW

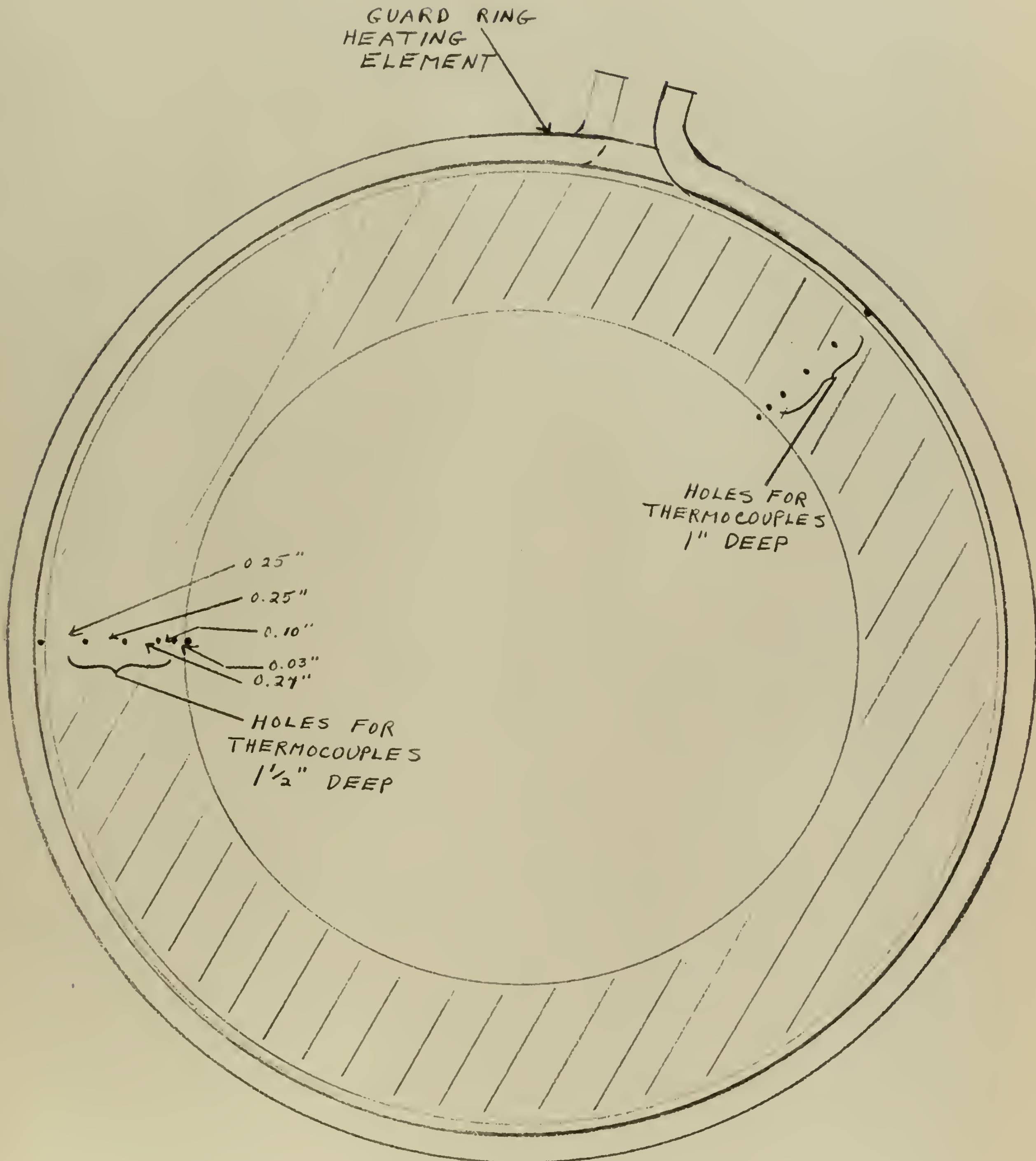


FIGURE 9

first at a depth of one inch and with spacing between holes as in the first series.

Readings of the six thermocouples in each series (one bead was soldered to the inner side and one to the outer side of the guard ring) were taken during a test as the ring warmed up to match the side temperatures of the heater disc. Fig. 10 graphically shows the distribution of temperatures in the two series at various times. The warmer temperature at the outer edge where the heating element touched the guard ring has apparently little influence on the constant temperature through the ring thickness. Equilibrium conditions were closely approached at time 1445 and again at 1653 after setting a higher electrical input for the disc and guard ring circuits. Corresponding thermocouple readings are included in Table 1 in the Appendix.

With the metallic samples, variations of one to three degrees in the measured temperatures at different points on one face were noted throughout the tests. The samples were rotated in place between runs so that the grooves containing the thermocouples were not in the same position with relation to the central heaters and water inlet and outlet.

The pair of thermocouples which gave the largest differential reading continued to give the largest reading relative to the other pairs regardless of the rotation of the sample. Similarly, the other differential readings retained their order from highest to lowest, although the actual values differed on succeeding tests at the same electrical inputs. This variation could not be positively attributed to the thermocouples alone. Each individual thermocouple resistance had been checked with an ohmmeter, and the length of leads had been adjusted to give equal resistances within one per cent.

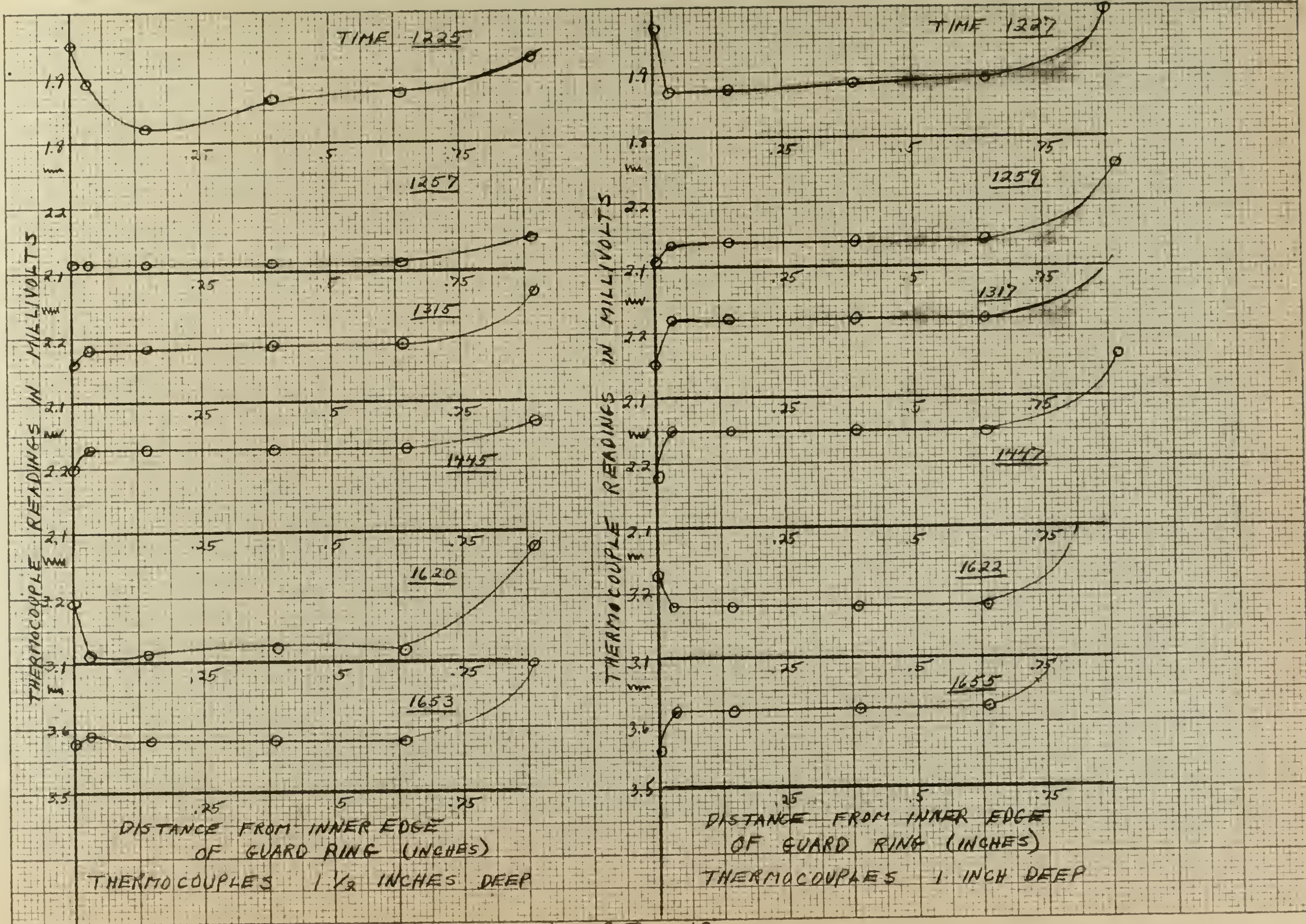

TIME 1225
1257
1315
1445
1620
1653
THERMOCOUPLE READINGS IN MILLIVOLTS
DISTANCE FROM INNER EDGE OF GUARD RING (INCHES)
THERMOCOUPLES 1 1/2 INCHES DEEP
TIME 1227
1259
1317
1447
1622
1655
THERMOCOUPLE READINGS IN MILLIVOLTS
DISTANCE FROM INNER EDGE OF GUARD RING (INCHES)
THERMOCOUPLES 1 INCH DEEP

FIGURE 10

Pressure distribution on the samples was somewhat varied during the series of tests as the C-clamps could not be placed in identical locations or with the exact same amount of compression in different runs. Another variable encountered is the position of the small thermocouple bead in the grooves provided. It is assumed that the center of the bead was at one-half of the groove depth. Not all the beads as formed by the flash welding process filled the groove, so slight variations in placement were expected.

4. Experimental results.

Using a thin layer of asbestos paper on each side of the sample in order to overcome the low emissivity of the smooth metallic faces, smaller temperature drops across the naval brass sample were obtained. The magnitude of these temperature differences gave calculated values of thermal conductivity which approached listed values in the Metals Handbook (12) and McAdams (10). The average of the differential readings for the sample on which four pair of thermocouples had been placed were used in computing k as shown in Table 3 in the Appendix. Tests were made with 100, 200, 300, and 400 watt inputs to the heating disc.

Because of the variation in the readings noted previously, the opposite brass sample was then used for comparative purposes. One groove was cut down the center of each face of this sample so that a pair of thermocouple beads could be placed at the exact center of each face, and another pair could be placed one inch out from the center. Results with 100 and 200 watt inputs to the center disc did not show good correlation with the previous results at the same electrical inputs.

For the 100 watt input, temperature drops across the top brass sample were 4.7, 4.6, 3.8, and 3.1 degrees, while at the center of the bottom sample the drop was 3.3 degrees, and at one inch out on the bottom sample the drop was 5.2 degrees. At an input of 200 watts, the corresponding readings were: top sample, 8.5, 8.3, 7.2, and 5.8 degrees; bottom center, 6.7 degrees; bottom one-inch out, 9.1 degrees. The data for the two pairs of thermocouples on the second sample is included in Table 2 in the Appendix with the data taken at the same time for the first brass sample.

In plotting the resulting values of thermal conductivity against the temperatures of the samples, consideration was given to the fact that the

calculated k value represents the average value over the range between the temperature on the warm face of the sample and that on the cool face. A bar on the graph (Fig. 11) is then more characteristic than a point at the middle of the temperature range for any one calculated value. There is a known rise in the value of k for brass as temperature increases. This is indicated by the graphical presentation given in the Metals Handbook (12) for the thermal conductivity of 70-30 brass (70% copper, 30% zinc) over the moderate temperature range. A curve showing this relation between k and temperature for this brass is shown in Fig. 11 for comparison with the experimental results with the naval brass sample.

Poor results such as obtained with the pair of thermocouples one inch out from the center of the bottom brass sample are not included in Fig. 11.

Stainless steel has a much lower value for k than does naval brass. Similar tests at 100, 200, 300, and 400 watt inputs were conducted with two stainless steel samples in the apparatus. One sample had two grooves machined down the center of the two faces to accommodate two pairs of thermocouples. The results of the runs where equilibrium conditions were closely approximated are shown in Fig. 12 and compared with tabulated values.

The 61S aluminum alloy samples were similarly placed in the apparatus with two pairs of thermocouples on the top sample. With the known value of $k = 99$ Btu/hr. ft. $^{\circ}$F. (12), a very small temperature difference across the sample was anticipated. Several attempts to obtain such small temperature drops (1.65 degrees for an electrical input of 100 watts to the heater disc) were unsuccessful, and no graphical presentation for the aluminum alloy is included.

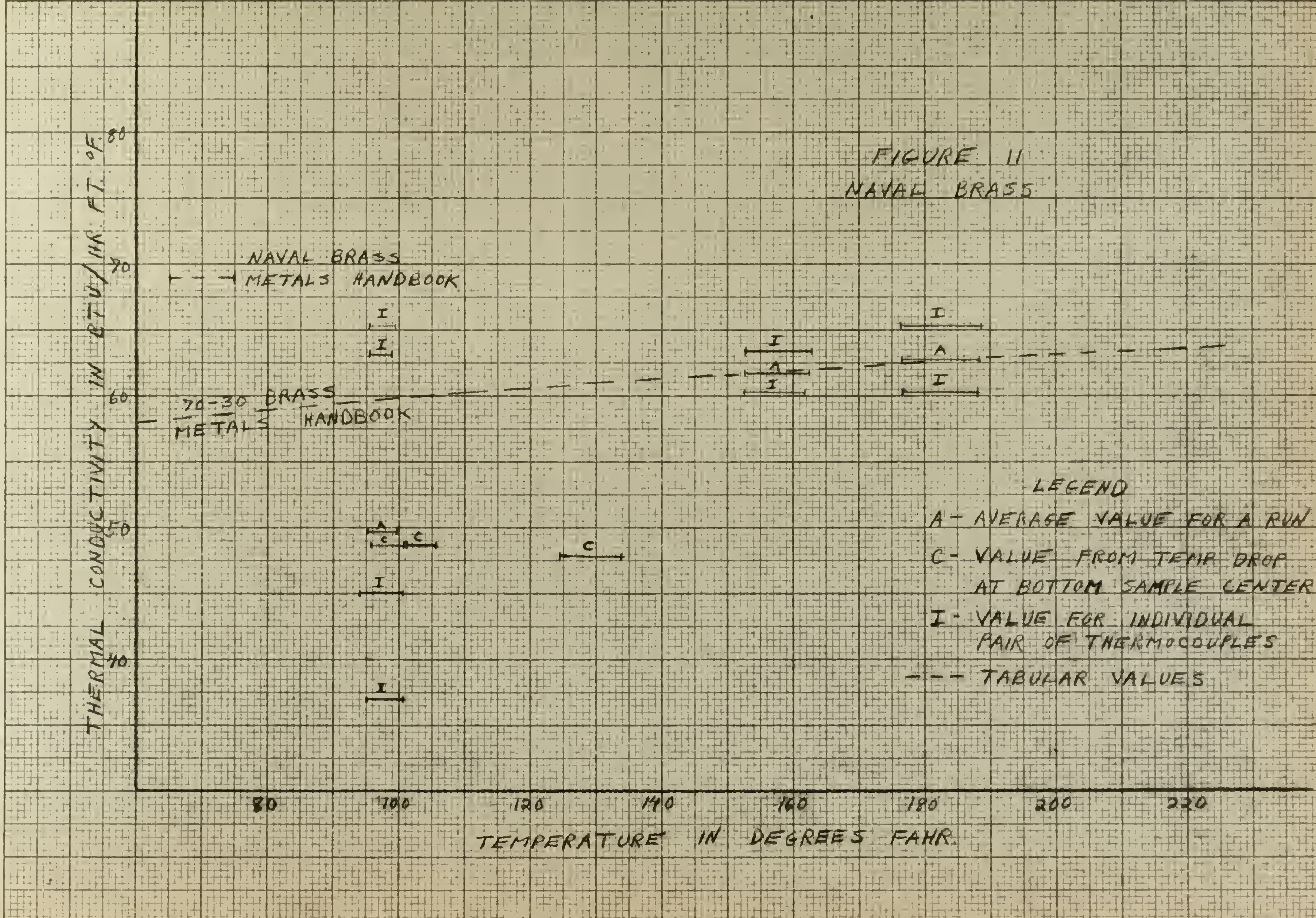


FIGURE 11
NAVAL BRASS
NAVAL BRASS
METALS HANDBOOK
70-30 BRASS
METALS HANDBOOK
LEGEND
A - AVERAGE VALUE FOR A RUN
C - VALUE FROM TEMP DROP AT BOTTOM SAMPLE CENTER
I - VALUE FOR INDIVIDUAL PAIR OF THERMOCOUPLES
--- TABULAR VALUES
THERMAL CONDUCTIVITY IN BTU/HR FT °F
TEMPERATURE IN DEGREES FAHR.
80
70
60
50
40
80
100
120
140
160
180
200
220

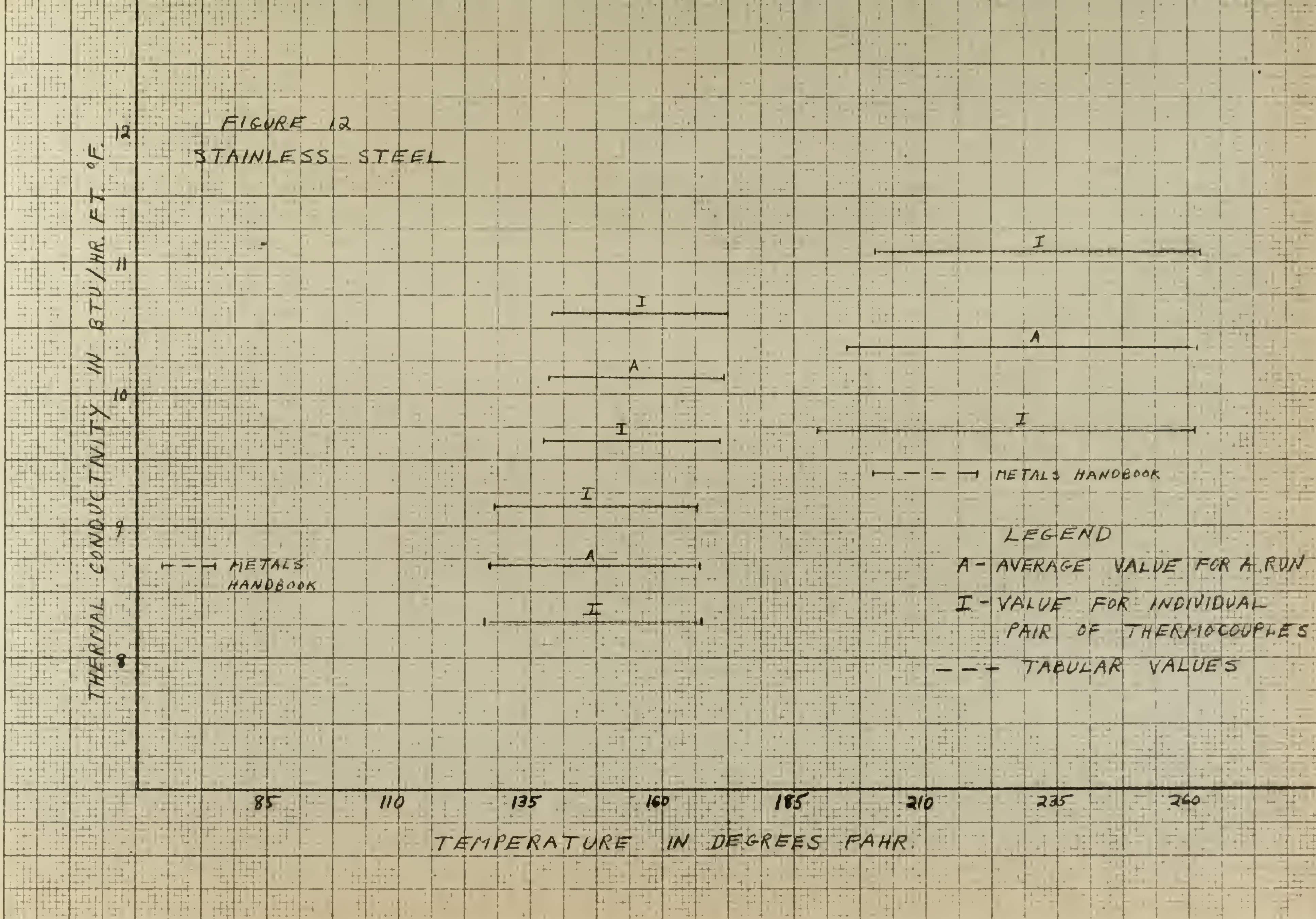


FIGURE 12
STAINLESS STEEL
THERMAL CONDUCTIVITY IN BTU/HR. FT. °F.
12
11
10
9
8
I
A
I
I
A
I
METALS HANDBOOK
I
A
I
METALS HANDBOOK
LEGEND
A - AVERAGE VALUE FOR A RUN
I - VALUE FOR INDIVIDUAL PAIR OF THERMOCOUPLES
TABULAR VALUES
85
110
135
160
185
210
235
260
TEMPERATURE IN DEGREES FAHR.

The asbestos paper on each side of the sample was also used with the insulating materials as well as with the metallic samples. Allowance for the 0.018 inch thickness of the paper was made in determining the best value of the thickness of the compressed insulating materials.

Results of the tests of asbestos sheet, corkboard, rubber, and leather are shown in the following graphs, Figures 13 to 16. Limitations in time available caused a choice of the low-input runs in these latter tests. The insulating powder was packed around the assembly in contrast to the tests of the alloys as early runs showed there was a leakage of about 40 to 50 per cent of the electrical input without the loose-fill powder. This estimate was based on the observed temperatures and tabulated values of k.

The calculated value for the thermal conductivity of the corkboard tested is consistently high over the range of temperatures encountered. It is assumed that the porosity and varying density of the cork as compressed did cause variations from the tabulated values for corkboard.

The asbestos sheet yielded results which were greater than listed values of thermal conductivity. The sheet is not as pliable as the other insulating materials tested. The air film between the asbestos samples and heater disc may have caused some heat leakage. Resulting temperature drops were lower than expected.

Because of the wide temperature ranges obtained for any one test of a non-metal, representation by bars of the average thermal conductivity is considered misleading. The points plotted are the values of average thermal conductivity at the mean temperature of the sample.

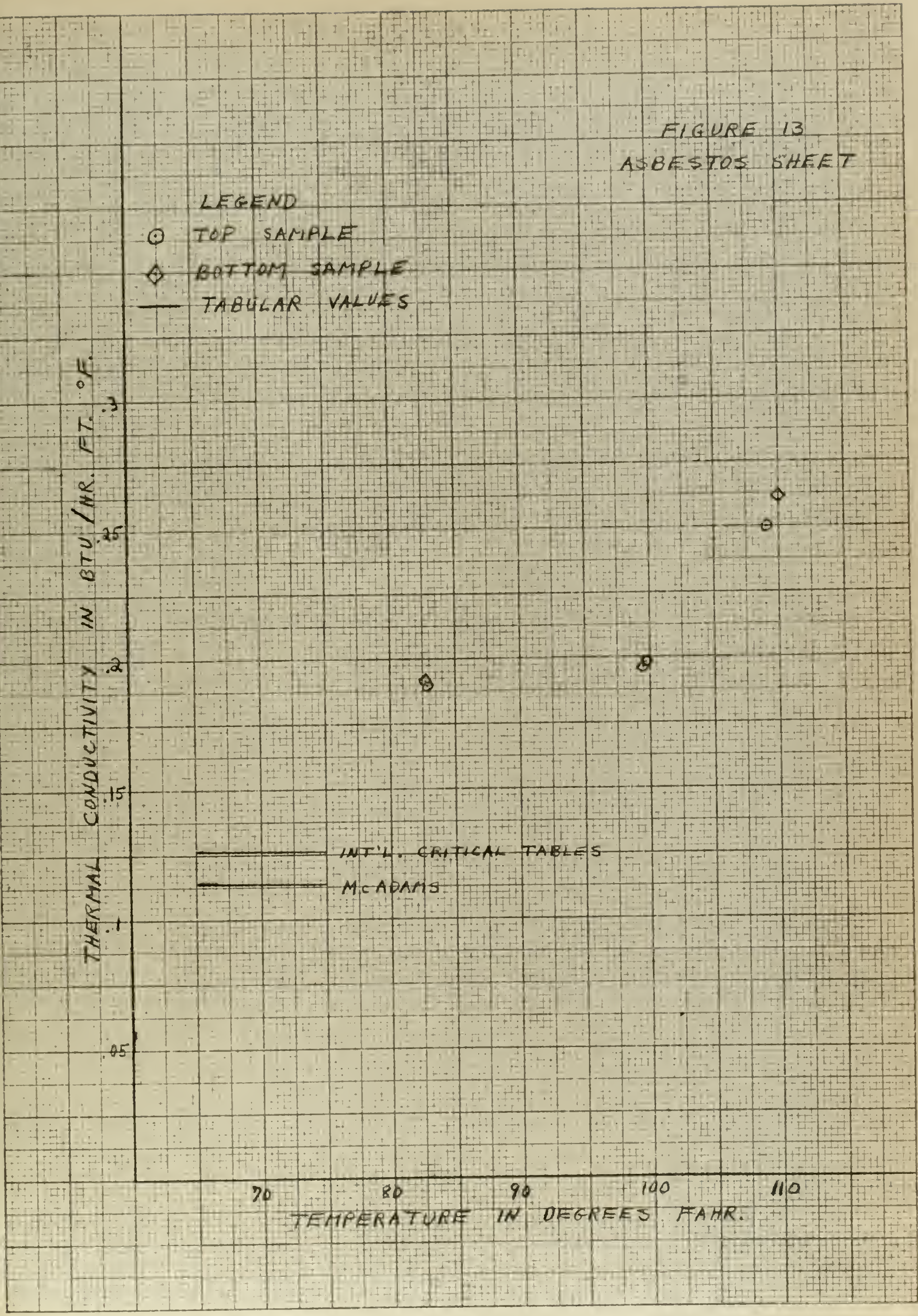
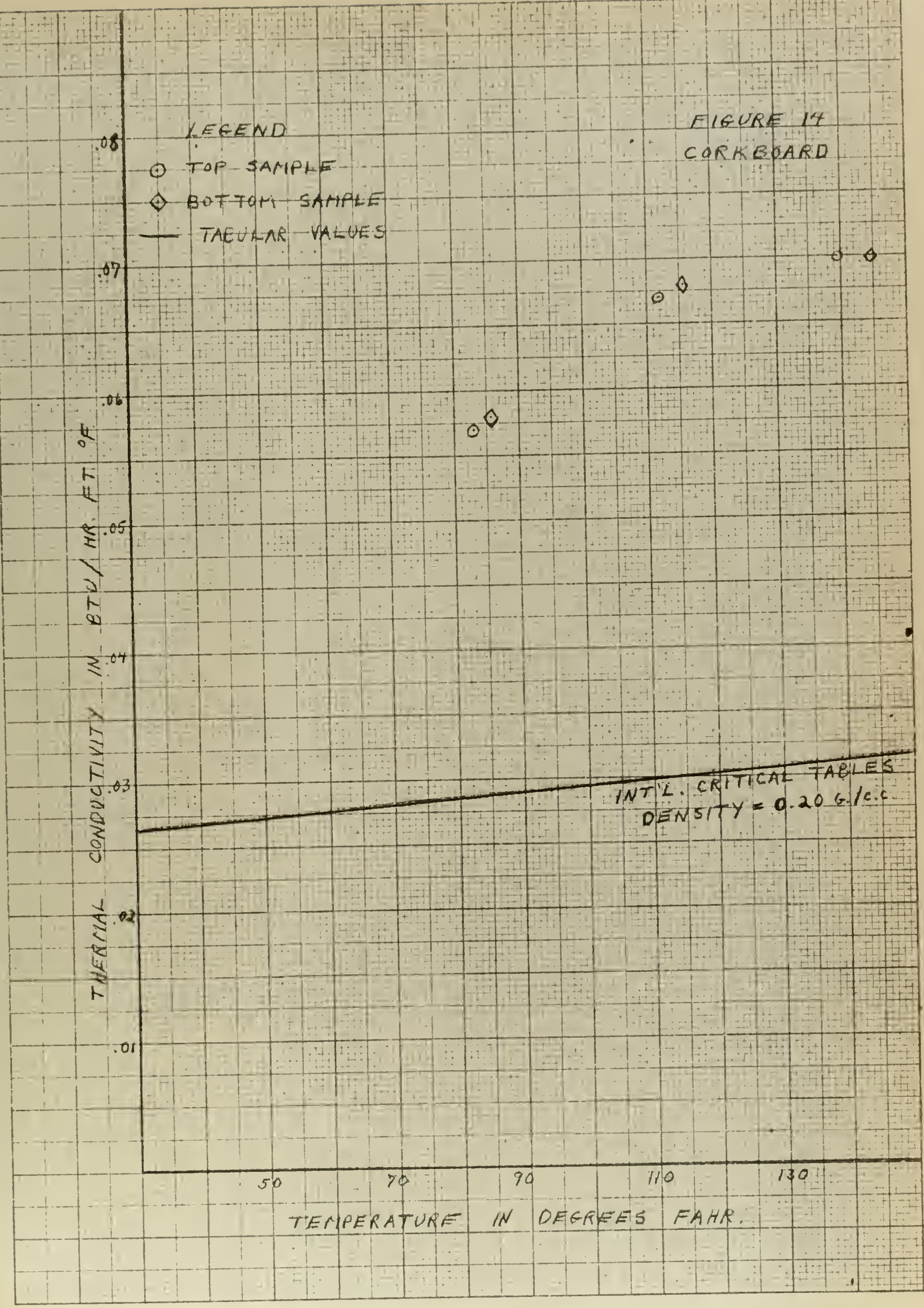
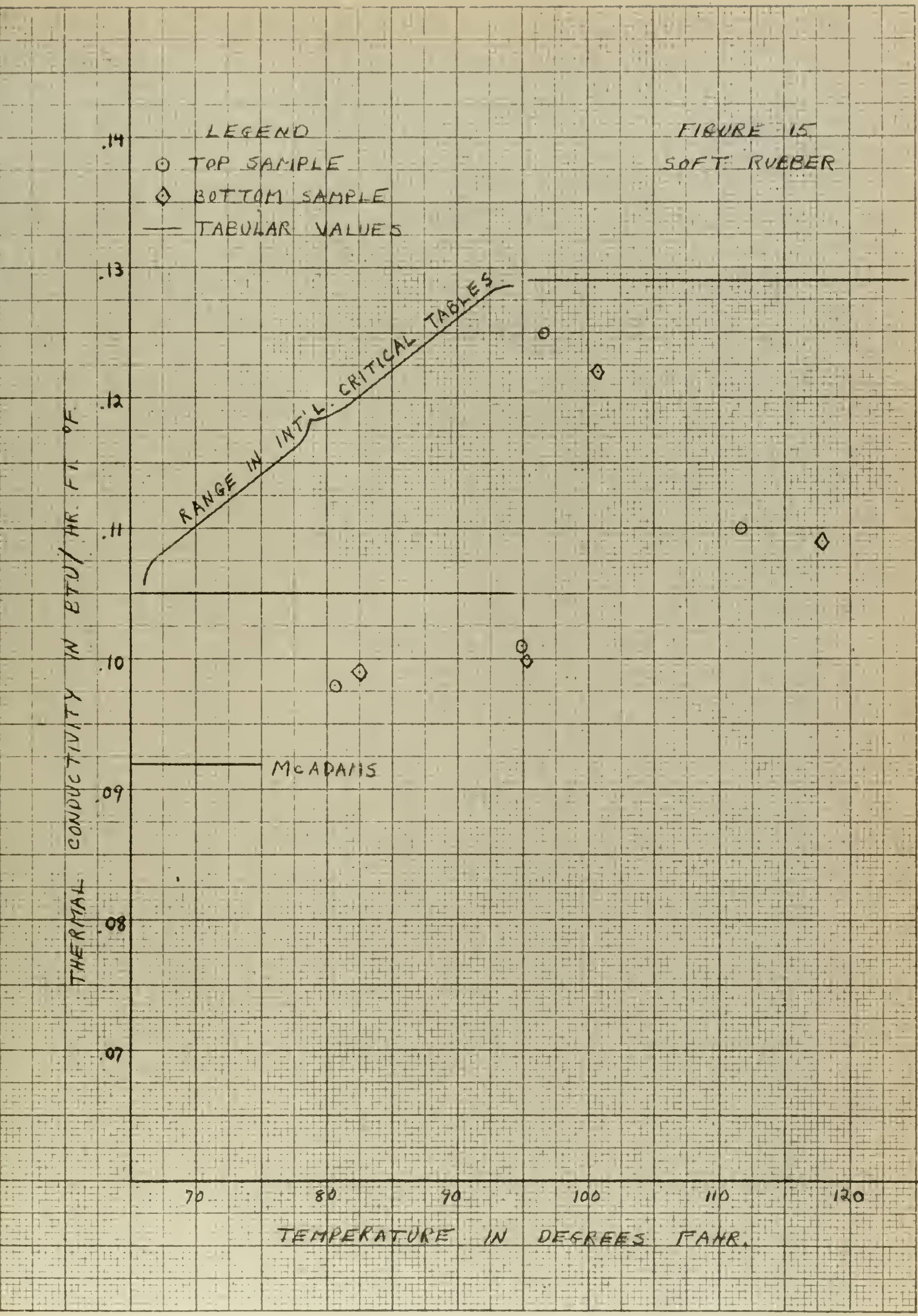


FIGURE 13
ASBESTOS SHEET
LEGEND
TOP SAMPLE
BOTTOM SAMPLE
TABULAR VALUES
THERMAL CONDUCTIVITY IN BTU/HR. FT. °F.
.3
.25
.2
.15
.1
.05
INT'L. CRITICAL TABLES
McADAMS
70
80
90
100
110
TEMPERATURE IN DEGREES FAHR.


LEGEND
TOP SAMPLE
BOTTOM SAMPLE
TABULAR VALUES
FIGURE 14
CORKBOARD
.08
.07
.06
.05
.04
.03
.02
.01
THERMAL CONDUCTIVITY IN BTU/HR. FT. °F
INT'L. CRITICAL TABLES
DENSITY = 0.20 G./c.c.
50
70
90
110
130
TEMPERATURE IN DEGREES FAHR.


LEGEND
TOP SAMPLE
BOTTOM SAMPLE
TABULAR VALUES
FIGURE 15
SOFT RUBBER
RANGE IN INT'L CRITICAL TABLES
McADAMS
.14
.13
.12
.11
.10
.09
.08
.07
THERMAL CONDUCTIVITY IN BTU/HR. FT °F
70
80
90
100
110
120
TEMPERATURE IN DEGREES FAHR.

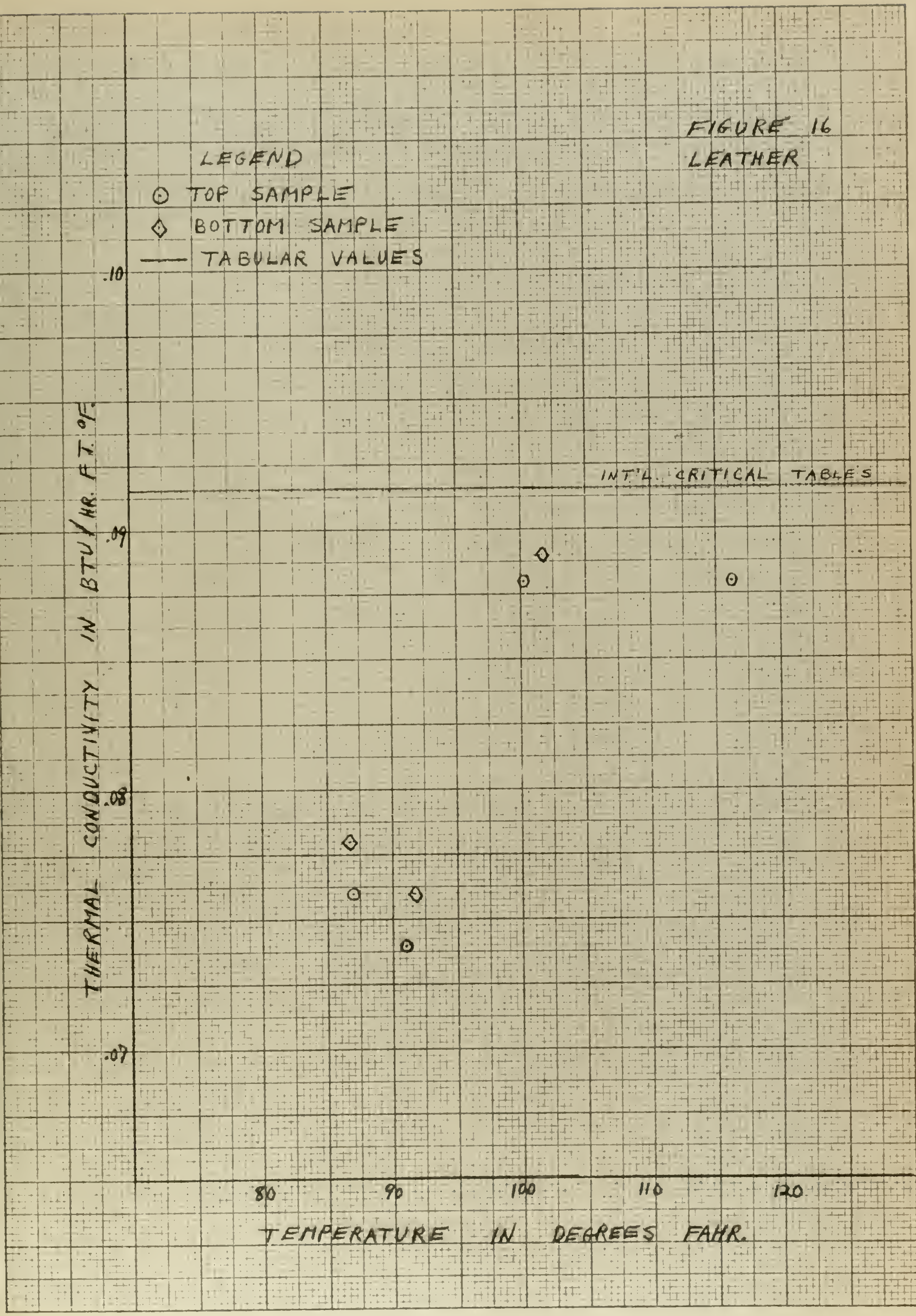


FIGURE 16
LEATHER
LEGEND
TOP SAMPLE
BOTTOM SAMPLE
TABULAR VALUES
INT'L. CRITICAL TABLES
THERMAL CONDUCTIVITY IN BTU/HR. FT. °F.
.10
.09
.08
.07
80
90
100
110
120
TEMPERATURE IN DEGREES FAHR.

The Appendix summarizes in Tables 2 and 3 the actual readings at the end of each test run when equilibrium conditions were approximated, and the data necessary to arrive at the values of thermal conductivity shown in the graphs accompanying this section.

5. Experimental uncertainties.

Accuracy of the readily measured quantities, i.e. thickness of samples, diameters, and electrical inputs was emphasized due to the deviations in the temperature measurements. Thicknesses were measured with the micrometer reading to the closest thousandth of an inch. Diameters were obtained with a steel rule graduated in multiples of 0.02 inches. For all calculations, it is assumed that the apparent contact area of the face is the actual product of $\pi/4$ and the square of the diameter.

Wattmeter readings were used for the values of electrical input to the central heater disc. The ammeter and voltmeter in each circuit were a check for the wattmeter. The product of the voltmeter and ammeter readings checked within less than two per cent of the wattmeter readings in the first test runs. For the latter runs, only the readings from the wattmeters, which were calibrated with a known resistance before installation in the circuits, were recorded. Errors in reading the wattmeters are estimated to be less than one per cent.

The cooling water temperature varied between 62 and 70 degrees Fahrenheit, based on random thermometer measurements at different times of day for different runs. Some measure of control was obtained by closing down on one of the two valves in the water discharge lines. Such throttling would cause rapid changes in the cooling plate temperatures. The difference in the average plate temperatures of the two cooling units could be kept within two degrees.

Experience showed that the Brown potentiometer gave an accuracy of within ten microvolts. This corresponded to 0.4 degrees Fahrenheit over the range of temperatures measured at the various samples. In averaging

the results from more than one pair of thermocouples per sample in the tests of metals, it is expected that accuracy was limited to the nearest half degree.

In the sample of calculations for the thermal conductivity of naval brass where the electrical input was 100 watts, uncertainties as outlined above would lead to the following errors:

Quantity	Uncertainty	Resulting error in k
Δx = 0.0812 ft.	0.001 in.	0.2%
A = 0.0864 sq. ft.	0.01 in. (diameter)	0.2%
q = 100 watts	1 watt	1%
Δt = 3.23 degrees	0.5 degrees	13.3%

For a thin slab of insulating material, the major uncertainty is the thickness measurement. The following table is for one sample calculation for the corkboard:

Quantity	Uncertainty	Resulting error in k
Δx = 0.096 in.	0.005 in.	5.4%
q = 20 watts	0.2 watts	1%
Δt = 51.3 degrees	0.5 degrees	0.8%

The slabs of non-metals covered more than the full area of the center disc face, and the area assumed for the calculations was that equivalent to a 4.00 inch diameter circle.

6. Conclusions.

The study of the various methods of measuring thermal conductivity and the ensuing design and test of one particular method has led the author to the following conclusions:

a. Results of testing metals are primarily dependent on accurate thermocouple readings. With low electrical inputs and where the temperature drop across a good thermal conductor is very small and approaches the limits for accuracy of the recording instruments, this guarded hot plate apparatus is not a satisfactory alternate to other known methods.

b. With care in measuring the thickness of the compressible insulating materials, good correlation in the calculated values of average thermal conductivity over a temperature range with tabulated values is obtainable.

c. As a laboratory demonstration, this apparatus can be successfully employed to show how the thermal conductivity of non-metals and poorly conducting metals can be determined.

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APPENDIX

Table 1. Results of Test of Temperature Variation Across Guard Ring (See Figure 10)

Series of Thermocouples $1\frac{1}{2}$ Inches Deep in Guard Ring

Time	1	2	3	4	5	6(Outermost)
1225	1.952	1.890	1.830	1.874	1.874	1.932 mv.
1257	2.114	2.114	2.111	2.114	2.112	2.155
1315	2.171	2.191	2.191	2.192	2.193	2.272
1445	2.204	2.232	2.232	2.232	2.232	2.268
1620	3.194	3.110	3.111	3.126	3.114	3.282
1653	3.583	3.590	3.580	3.580	3.580	3.700

Series of Thermocouples One Inch Deep in Guard Ring

Time	1	2	3	4	5	6(Outermost)
1227	1.966	1.874	1.874	1.884	1.884	2.032 mv.
1259	2.109	2.135	2.135	2.135	2.136	2.258
1317	2.156	2.218	2.218	2.219	2.221	2.424
1447	2.181	2.248	2.248	2.248	2.247	2.366
1622	3.230	3.180	3.180	3.181	3.181	3.526
1655	3.560	3.620	3.620	3.621	3.626	3.906

Data recorded on April 14, 1958

APPENDIX

Table 2. Steady State Test Data

Naval Brass Samples

Run	1	2	3	4
Elec. input to disc	100 w.	200 w.	300 w.	400 w.
Elec. input to ring	30 w.	50 w.	110 w.	150 w.
Temps. in millivolts				
Top cooling plate	0.874	1.075	1.247	1.454
Top face-upper sample	1.360	2.037 2.028 2.029	2.780 2.740 2.778	3.364 3.358 3.374
Bottom face-upper sample	1.443	2.186 2.185 2.210 2.198	3.044 3.020 3.058 3.000	3.758 3.680 3.816 3.662
Top face-heater disc	2.004	3.358	4.972	6.258
Bottom face-heater disc	2.004	3.380	5.011	6.285
Bottom cooling plate	0.906	1.109	1.322	1.494
Outer edge of disc	2.066 2.097	3.369 3.358	5.134 5.176	6.402 6.460
Inner edge of guard ring	2.104 2.087	3.259 3.251	5.140 5.086	6.372 6.326
Drop across sample (Differential rdg.)	0.076	0.128 0.148 0.155	0.190 0.200	0.246 0.266

Table 2 (Continued)

Naval Brass Samples

Run	5	6	7	8
Elec. input to disc	100 w.	100 w.	200 w.	100 w.
Elec. input to ring	25 w.	25 w.	60 w.	25 w.
Temps. in millivolts				
Top cooling plate	0.920	0.937	1.112	0.983
Top face-upper sample	1.400	1.358	1.986	1.491
	1.413	1.375	2.034	1.530
	1.382	1.347	2.000	1.408
	1.413	1.359	2.002	1.499
Bottom face-upper sample	1.528	1.469	2.222	1.614
	1.498	1.455	2.207	1.602
	1.526	1.458	2.212	1.608
	1.491			
Top face-heater disc	2.095	1.976	3.326	2.157
Bottom face-heater disc	2.106	1.975	3.326	2.152
Top face-bottom sample				
At center		1.532	2.315	1.650
At 1 inch out		1.555	2.367	1.668
Bottom face-bottom sample				
At center		1.420	2.092	1.539
At 1 inch out		1.367	1.988	1.507
Bottom cooling plate	0.927	0.967	1.112	0.986
Outer edge of disc	2.144	1.984	3.397	2.174
	2.165	2.022	3.440	2.206
Inner edge of guard ring	2.169	1.984	3.425	2.091
	2.162	1.964	3.430	2.113
Drop across sample	0.104	0.106	0.201	0.123
(Differential rdg.)	0.059	0.072	0.139	0.062
	0.086	0.108	0.201	0.216
	0.061	0.087	0.173	0.101
Average - top sample	0.078	0.093	0.178	0.126
Center-bottom sample		0.076	0.159	0.076
1" out-bottom sample		0.119	0.218	0.115

Table 2 (Continued)

Stainless Steel Samples

Run	1	2	3	4
Elec. input to disc	100 w.	200 w.	300 w.	400 w.
Elec. input to ring	40 w.	90 w.	145 w.	300 w.
Temps. in millivolts				
Top cooling plate	0.904	1.214	1.423	1.499
		1.164	1.350	
Top face-upper sample				
At center	1.417	2.182	2.912	3.974
At 1 inch out	1.404	2.137	2.826	3.701
Bottom face-upper sample				
At center	1.866	3.116	4.322	5.613
At 1 inch out	1.911	3.148	4.378	5.586
Top face-heater disc	2.412	4.200	6.043	8.214
Bottom face-heater disc	2.400	4.204	6.042	8.098
		4.162	5.960	7.995
Bottom cooling plate	0.866	1.132	1.306	1.566
		1.160	1.354	1.876
Outer edge of disc	2.484	4.284	6.090	8.310
	2.520	4.332	6.170	8.388
Inner edge of guard ring	2.580	4.306	6.012	8.363
	2.575	4.324	6.056	8.378
Drop across sample (Differential rdg.)				
Center	0.415	0.856	1.314	1.556
1 inch out	0.466	0.944	1.448	1.766
Average	0.440	0.900	1.381	1.661

Table 2 (Continued)

Run	Stainless Steel 5	Stainless Steel 6	Aluminum (61S) 1	Aluminum (61S) 2	Aluminum (61S) 3
Elec. input to disc	100 w.	200 w.	100 w.	200 w.	300 w.
Elec. input to ring	50 w.	90 w.	20 w.	75 w.	150 w.
Temps. in millivolts					
Top cooling plate	0.924	1.089	0.976	1.134	1.297
			0.961	1.096	1.231
Top face-upper sample					
At center	1.587	2.397	1.524	2.286	3.010
At 1 inch out	1.649	2.502	1.516	2.267	2.997
Bottom face-upper sample					
At center	2.001	3.235	1.678	2.620	3.540
At 1 inch out	2.017	3.266	1.680	2.609	3.531
Top face-heater disc	2.574	4.419	2.157	3.771	5.349
			2.186	3.805	5.397
Bottom face-heater disc	2.546	4.358	2.156	3.729	5.265
	2.533	4.302	2.175	3.793	5.388
Bottom cooling plate	0.924	1.075	0.994	1.065	1.196
	0.973	1.171	1.053	1.128	1.300
Outer edge of disc	2.669	4.456	2.047	3.854	5.690
	2.776	4.500	2.043	3.908	5.694
Inner edge of guard ring	2.946	4.440	1.820	3.862	5.820
	2.910	4.464	1.916	3.879	5.762
Drop across sample (Differential rdg.)					
Center	0.396	0.809	0.074	0.162	0.232
1 inch out	0.360	0.737	0.088	0.184	0.273
Average	0.378	0.773	0.081	0.173	0.252

Table 2 (Continued)

Asbestos Sheet Samples
(No asbestos paper used)

Run	1	2	3	4
Elec. input to disc	50 w.	25 w.	100 w.	75 w.
Elec. input to ring	125 w.	50 w.	125 w.	125 w.
Temps. in millivolts				
Top cooling plate & top-upper sample	0.950	0.816	1.229 1.092	1.160 1.099
Top face-heater disc & bottom-upper sample	2.096 2.076	1.433 1.427	2.464	2.343
Bottom face-heater disc & top-bottom sample	2.084 2.074	1.419 1.428	2.442 2.514	2.340 2.329
Bottom cooling plate & bottom-bottom sample	0.943 0.950	0.828 0.804	1.136 1.130	1.230 1.129
Outer edge of disc	2.109 2.084	1.432 1.459	2.414 1.940	2.353 2.122
Inner edge of guard ring	2.109 2.080	1.431 1.416	1.932 2.212	2.113 2.255
Drop across sample (Differential rdg.)				
Top sample	1.160	0.606	1.516	1.385
Bottom sample	1.163 1.171	0.606 0.604	1.454 1.433	1.322

Table 2 (Continued)

Corkboard Samples

Run	1	2	3	4
Elec. input to disc	20 w.	10 w.	30 w.	50 w.
Elec. input to ring	25 w.	15 w.	35 w.	55 w.
Temps. in millivolts				
Top cooling plate	0.860 0.917	0.850 0.883	0.861 0.936	0.917 1.040
Top face-upper sample	0.972	0.903	0.999	1.135
Bottom face-upper sample	2.181	1.512	2.624	3.875
Top face-heater disc	2.376	1.610	2.893 2.844	4.343
Bottom face-heater disc	2.370 2.376	1.607 1.607	2.888 2.888	4.332 4.339
Top face-bottom sample	2.226	1.537	2.697	3.999
Bottom face-bottom sample	1.009	0.944	1.098	1.252
Bottom cooling plate	0.871 0.858	0.900 0.862	0.974 0.890	0.961 0.932
Outer edge of disc	2.469 2.470	1.646 1.644	2.860 2.908	4.281 4.368
Inner edge of guard ring	2.589 2.578	1.692 1.686	2.906 2.919	4.350 4.373
Drop across samples (Differential rdg.)				
Top sample	1.190	0.625	1.632	2.718
Bottom sample	1.227	0.610	1.605	2.729

Table 2 (Continued)

Soft Rubber Samples

Run	1	2	3	4
Elec. input to disc	10 w.	30 w.	60 w.	30 w.
Elec. input to ring	25 w.	75 w.	165 w.	100 w.
Temps. in millivolts				
Top cooling plate	0.858 0.851	0.875 0.908	0.966 1.014	0.908 0.948
Top face-upper sample	0.917	0.968	1.146	1.001
Bottom face-upper sample	1.240	1.699	2.730	1.882
Top face-heater disc	1.422 1.424	1.915 1.924	3.182 3.201	2.160 2.168
Bottom face-heater disc	1.420 1.424	1.914 1.922	3.183 3.201	2.156 2.167
Top face-bottom sample	1.303	1.775	2.889	1.986
Bottom face-bottom sample	0.933	1.046	1.334	1.090
Bottom cooling plate	0.896 0.848	0.888 0.919	1.006 0.949	1.029 0.937
Outer edge of disc	1.454	1.926	3.182	2.498
Inner edge of guard ring	1.476 1.460	1.935 1.934	3.198 3.203	2.529 2.464
Drop across sample (Differential rdg.)				
Top sample	0.339	0.746	1.588	0.899
Bottom sample	0.384	0.744	1.557	0.916

Table 2 (Continued)

Soft Rubber Samples

Run	5	6	7
Elec. input to disc	10 w.	20 w.	40 w.
Elec. input to ring	30 w.	55 w.	100 w.
Temps. in millivolts			
Top cooling plate	0.864 0.886	0.907 0.954	0.994 1.044
Top face-upper sample	0.895	0.970	1.112
Bottom face-upper sample	1.252	1.697	2.485
Top face-heater disc	1.360 1.363	1.920 1.925	2.908 2.916
Bottom face-heater disc	1.358 1.363	1.912 1.924	2.900 2.914
Top face-bottom sample	1.292	1.776	2.648
Bottom face-bottom sample	0.936	1.040	1.254
Bottom cooling plate	0.928 0.884	1.023 0.924	1.185 1.033
Outer edge of disc	1.523	2.262	3.356
Inner edge of guard ring	1.539 1.512	2.298 2.232	3.396 3.320
Drop across sample (Differential rdg.)			
Top sample	0.376	0.740	1.388
Bottom sample	0.372	0.747	1.402

Table 2 (Continued)

Leather Samples

Run	1	2	3	4	5
Elec. input to disc	20 w.	30 w.	10 w.	20 w.	10 w.
Elec. input to ring	40 w.	35 w.	15 w.	30 w.	10 w.
Temps. in millivolts					
Top cooling plate	0.818 0.854	0.850 0.870	0.898 0.887	0.838 0.829	0.807 0.799
Top face-upper sample	0.872	0.906	0.928	0.873	0.826
Bottom face-upper sample	2.023	2.930	1.697	2.195	1.569
Top face-heater disc	2.124	3.112 3.078	1.744 1.791	2.275 2.275	1.609
Bottom face-heater disc	2.124 2.136	3.112 3.122	1.744 1.770	2.274 2.283	1.609 1.598
Top face-bottom sample	-	-	1.708	2.214	1.582
Bottom face-bottom sample	0.906	0.968	0.948	0.912	0.848
Bottom cooling plate	0.855 0.821	0.896 0.851	0.912 0.914	0.850 0.860	0.807 0.815
Outer edge of disc	2.182 2.197	3.121 3.137	1.796 1.784	2.287 2.296	1.577 1.601
Inner edge of guard ring	2.327 2.286	3.140 3.140	1.848 1.834	2.327 2.317	1.575 1.575
Drop across sample (Differential rdg.)					
Top sample	1.142	2.036	0.789	1.336	0.757
Bottom sample	-	-	0.770	1.312	0.744

APPENDIX

Table 3. Data for Determination of Thermal Conductivity

Naval Brass Samples

Thickness of sample	0.999 in. = 0.0832 ft.
Allowance for grooves	2(0.0125) = 0.025 in.
Assumed thickness	0.974 in. = 0.0812 ft.
Diameter of sample	3.99 in.
Area of sample face	0.0864 sq. ft.
Multiplying factor	3.21

Run	Disc input		Temp. drop	k	Temp. range
1	100 w.		3.32°F.	48.3	96.8-93.2°F.
2	200 w.		5.33		
			6.16		
			6.46		
			6.00-av.	53.5*	128.7-121.9
3	300 w.		7.60	63.4	162.5-152.8
			8.00	60.2	161.7-152.7
			7.80-av.	61.7	162.1-152.8
4	400 w.		9.84	65.3	188.8-176.3
			10.64	60.3	188.0-176.7
			10.24-av.	62.7	188.4-176.5
5	100 w.		4.33	37.1	100.5-95.0
			2.46	65.3	99.2-95.5
			3.58	44.9	100.4-94.2
			2.54	63.2	98.9-95.5
			3.23-av.	49.7	99.8-95.0
6	100 w.		4.61		
			3.14		
			4.69		
			3.78		
			3.88-av.	41.3*	97.5-93.2
		Center-bottom s.	3.30	48.6	100.7-95.8
		1" out-bottom s.	5.17	31.0*	101.7-93.5

*Poor results or non-equilibrium conditions-value not shown in Fig. 11.

Table 3 (Continued)

Naval Brass Samples

Run	Disc input		Temp. drop	k	Temp. range
7	200 w.		8.36°F.		
			5.79		
			8.36		
			7.20		
			7.45-av.	43.1*	129.5-120.8°F.
		Center-bottom s.	6.70	47.9	133.7-124.4
		1" out-bottom s.	9.12	35.2*	135.9-120.0
8	100 w.		5.23		
			2.64		
			4.30		
			3.97-av.	40.4*	103.9-98.5°F.
		Center-bottom s.	3.30	48.6	105.7-101.0
		1" out-bottom s.	5.00	32.1*	106.5-99.6

*Poor results or non-equilibrium conditions-value not shown in Fig. 11.

Stainless Steel Samples

Thickness of sample	1.000 in. =	0.0833 ft.
Allowance for grooves	2(0.0125) =	0.025 in.
Assumed thickness	0.975 in. =	0.0813 ft.
Diameter of sample	4.00 in.	
Area of sample face	0.0871 sq. ft.	
Multiplying factor	3.185	

Run	Disc input		Temp. drop	k	Temp. range
1	100 w.	Center	17.3°F.		
		1" out	19.5		
		Average	18.4	8.65*	115.8-95.4°F.
2	200 w.	Center	34.8	9.15	166.4-128.2
		1" out	38.5	8.27	167.6-126.2
		Average	36.6	8.70	167.0-127.2

*Poor results or non-equilibrium conditions-value not shown in Fig. 12.

Table 3 (Continued)

Stainless Steel Samples

Run	Disc input		Temp. drop	k	Temp. range
3	300 w.	Center	50.5°F.		
		1" out	55.6		
		Average	53.0	9.01*	214.8-156.4°F.
4	400 w.	Center	57.5	11.08	262.3-200.3
		1" out	65.5	9.72	261.3-189.6
		Average	61.5	10.35	261.8-195.0
5	100 w.	Center	16.3		
		1" out	15.2		
		Average	15.8	10.08*	121.4-104.6
6	200 w.	Center	33.0	9.65	171.1-137.1
		1" out	30.0	10.61	172.4-141.4
		Average	31.5	10.12	171.8-139.2

*Poor results or non-equilibrium conditions-value not shown in Fig. 12.

Aluminum Samples

Thickness of sample 0.994 in. = 0.0829 ft.

Allowance for grooves 2(0.0125) = 0.025 in.

Assumed thickness 0.968 in. = 0.0808 ft.

Diameter of sample 4.00 in.

Area of sample face 0.0871 sq. ft.

Multiplying factor 3.16

Run	Disc input		Temp. drop	k	Temp. range
1	100 w.	Center	3.22°F.		
		1" out	3.82		
		Average	3.52	44.6*	107.0-100.2°F.
2	200 w.	Center	6.75		
		1" out	7.67		
		Average	7.21	43.8*	146.0-132.1
3	300 w.	Center	9.28		
		1" out	10.92		
		Average	10.10	46.9*	183.0-161.8

*Inconclusive results-value not plotted.

Table 3 (Continued)

Asbestos Sheet Samples

Thickness of sample = 0.123 in. (No allowance was made for asbestos paper as it was not used with the asbestos sheet samples)
= 0.0102 ft.

Assumed area of sample face in contact with heater face = 0.0871 sq. ft.

Multiplying factor = 0.399

Run	Disc input		Temp. drop	k	Temp. range	Mean temp.
1	50 w.	Top sample	50.6°F.	0.198	124.5-75.3°F.	99.6°F.
		Bottom sample	50.8	0.197	123.8-75.2	99.5
2	25 w.	Top	26.4	0.190	96.4-69.3	82.8
		Bottom	26.2	0.191	96.0-69.3	82.6
3	100 w.	Top	66.0	0.304*	139.9-84.5	112.2
		Bottom	62.8	0.320*	140.5-83.3	111.9
4	75 w.	Top	60.3	0.250	134.9-83.2	109.0
		Bottom	57.5	0.262	134.8-83.1	110.0

*Poor results or non-equilibrium conditions-value not shown in Fig. 13.

Corkboard Samples

Thickness of sample = 0.126 in.

Allowance for asbestos paper = 0.030 in.

Assumed thickness = 0.096 in. = 0.008 ft.

Assumed area of sample face in contact with heater face = 0.0871 sq. ft.

Multiplying factor = 0.312

Run	Disc input		Temp. drop	k	Temp. range	Mean temp.
1	20 w.	Top sample	51.3°F.	0.061*	128.1-76.2°F.	102.2°F.
		Bottom sample	51.3	0.061*	130.0-77.9	104.0
2	10 w.	Top	27.4	0.057	99.8-73.2	86.5
		Bottom	26.8	0.058	100.9-75.0	87.9

*Non-equilibrium conditions-value not shown in Fig. 14.

Table 3 (Continued)

Corkboard Samples

Run	Disc input		Temp. drop	k	Temp. range	Mean temp.
3	30 w.	Top sample	69.5°F.	0.067	146.4-77.4°F.	111.9°F.
		Bottom sample	68.4	0.068	149.4-81.8	115.6
4	50 w.	Top	111.0	0.070	195.2-83.3	139.3
		Bottom	111.4	0.070	200.1-88.5	144.3

Soft Rubber Samples

Thickness of sample = 0.130 in.

Allowance for asbestos paper = 0.030 in.

Assumed thickness = 0.100 in. = 0.0083 ft.

Assumed area of sample face in contact with heater face = 0.0871 sq. ft.

Multiplying factor = 0.325

Run	Disc input		Temp. drop	k	Temp. range	Mean temp.
1	10 w.	Top sample	15.1°F.	0.107*	88.0-73.8°F.	80.9°F.
		Bottom sample	17.1	0.095*	90.7-74.5	82.6
2	30 w.	Top	32.5	0.150*	107.8-76.0	91.9
		Bottom	32.3	0.151*	111.0-79.5	95.2
3	60 w.	Top	66.2	0.147*	150.8-83.9	117.4
		Bottom	64.8	0.150*	157.2-92.1	124.6
4	30 w.	Top	39.1	0.125	115.5-77.5	96.5
		Bottom	39.8	0.122	120.0-81.4	100.7
5	10 w.	Top	16.6	0.098	88.5-72.8	80.6
		Bottom	16.4	0.099	90.3-74.7	82.5
6	20 w.	Top	32.2	0.101	107.7-76.1	94.9
		Bottom	32.5	0.100	111.1-79.2	95.2
7	40 w.	Top	58.8	0.110	140.8-82.4	111.6
		Bottom	59.5	0.109	147.4-88.6	117.8

*Poor results or non-equilibrium conditions-value not shown in Fig. 15.

Table 3 (Continued)

Leather Samples

Thickness of sample = 0.185 in.

Allowance for asbestos paper = 0.030 in.

Assumed thickness = 0.155 in. = 0.0130 ft.

Assumed area of sample face in contact with heater face = 0.0871 sq. ft.

Multiplying factor = 0.504

Run	Disc input		Temp. drop	k	Temp. range	Mean temp.
1	20 w.	Top sample	49.3°F.	0.102*	121.5-71.8°F.	96.6°F.
2	30 w.	Top	85.9	0.088	158.9-73.3	116.1
3	10 w.	Top	34.3	0.074	107.7-74.3	91.0
		Bottom sample	33.4	0.076	108.2-75.2	91.7
4	20 w.	Top	57.6	0.088	128.7-71.8	100.2
		Bottom	56.6	0.089	129.5-73.6	101.6
5	10 w.	Top	33.0	0.076	102.2-69.7	87.0
		Bottom	32.4	0.078	102.8-70.7	86.7

*Non-equilibrium conditions-value not shown in Fig. 16.